An Integrated Approach to the Remediation and Management of Coastal Acid Sulfate Soils

Lance Clive Heath

Centre for Resource and Environmental Studies

June, 2004

A Thesis submitted for the degree of Doctor of Philosophy
The Australian National University

STATEMENT

I hereby declare that, to the best of my knowledge, this thesis represents original and independent research except where it is stated in the text or as indicated below.

The ANUSPLIN suite of programs and ANUDEM were written by Professor Mike Hutchinson from the Centre for Resource and Environmental Studies, Australian National University.

The "Carbon Farmer" accounting package was developed by Hassall and Associates for the Rural Industries Research and Development Corporation. The STL Program in S-Plus was used in the rainfall analysis.

The Electronic Content Management System was developed by a Canberra based company, Millpost Technologies Pty Ltd. The development of the MySQL database for the Geographic Decision Support System (GDSS), was carried out by Mr Mark Kerr from Millpost Technologies Pty Ltd, using my specifications and under my supervision.

(Lance Heath)

ACKNOWLEDGEMENTS

I would like to begin by thanking my supervisor Professor Ian White for his encouragement and interest he has shown in this work. He is a great friend and colleague. I would also like to express my sincere thanks and appreciation to the other members on my supervisory panel. I have been fortunate to have had Professor Mike Hutchinson for his climatological advice and for his help in using the interpolation programs he had developed. Professor Mike Melville from the University of New South Wales for always providing an interesting and at times, stimulating environment on all aspects relating to acid sulfate soils and Dr Sara Beavis for her support and encouragement throughout my course of study.

There are many other people at the Centre for Resource and Environmental Studies (CRES) who I would like to thank and who have made this research possible. Ms Kathy Hicks for her support and encouragement. Mr Mark Greenaway and Mr Phil Greaves for their computing support and Mr Karl Nissen for his help with the GIS component of the project. I am particularly indebted to Mr John Stein and Mrs Janet Stein who provided many hours of their time in helping me when things went terribly wrong or when I needed advice. I would also like to thank Dr Ken Johnson and Dr Jeanette Lindesay for their intellectual stimulus on all aspects of climate modelling and Dr Ben Macdonald for his support and kindness in sharing his house during my field trips to the Tweed. A sincere thanks to Dr Steven Dovers for his advice on issues concerning environmental accounting and economics.

I am also grateful to Mr Mark Tunks from the Tweed Shire Council and his team for their support in providing the data for analysis. And to Mr Robert Quirk for allowing me to invade his property.

Special thanks to my brother, Dr Stephen Heath for his valuable comments on the manuscript and my wife Dianne, for her help with the endless multitude of Microsoft Excel spreadsheets.

Last but not least, I would especially like to thank my wife Dianne and my daughter Laura for their support and friendship and for putting up with my frustration (at times). I would also like to give a special thanks to my parents Marge and John Heath (and in particular to my father who is now faced with a dreadful illness) for their continued support and encouragement throughout my education and life in general.

Of course this project would not have been possible without the assistance of the NSW Department of Agriculture (ASSPRO). The funding assistance has been greatly appreciated.

ABSTRACT

This thesis used an integrated approach for the management and remediation of acid sulfate soil landscapes. It considered the broader implications of climate and land management changes, as well as the economic and social influences that affect management decisions at the catchment scale.

An integral part of this thesis was the development of a Geographic Information System (GIS). The GIS incorporates a water quality hydrological model to predict acid outflows in response to climate and land management decisions. The GIS hydrological water quality model was used to assess the effectiveness of remediation strategies for the Cudgen Catchment in northern NSW. The strategies considered here included capping, the in-filling of drains and the reduction and diversion of surface water flows. It was concluded that two or more strategies were required to effectively reduce acid surface water loads to Cudgen Lake. The costs of remediation were shown to be relatively small compared to the benefits derived from ecosystem services. For the Cudgen Catchment, land owners need to consider alternative land use practices that will reduce acidification and improve water quality for Cudgen Lake.

The thesis also examined the long-term rainfall variability in the Tweed and its impact on fish life. Rainfall variability in the Tweed is strongly influenced by global climate systems such as El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Although the PDO is a strong modulator of ENSO activity, its relationship to Tweed rainfall is weak and is therefore not a reliable forecaster of rainfall variability. There was a strong association between rainfall variability in the Tweed and the Southern Oscillation (SO), which operates on decadal time scales. Statistical analysis showed a distinct shift in rainfall seasonality since the 1980s. This shift shows drier conditions for late summer and wetter conditions for late autumn. The results also showed that fish kills are closely linked to El Niño-Southern Oscillation (ENSO) cycles. A fish kill emergency management forecaster planner was developed for the Tweed.

The National Strategy for the management of Acid Sulfate Soils highlighted the importance of improved communication strategies. Here, two on-line communication systems were employed to demonstrate the effective use of recent information and communication technology and its role in acid sulfate soil management. These systems include an Electronic Content Management System (ECMS) and an on-line Geographic Decision Support System (GDSS) to provide improved access to information about acid sulfate soils and drain management.

TABLE OF CONTENTS

CHAPTER 5

THE CUDGEN CATCHMENT: A BASELINE STUDY

CHAPTER 7

RAINFALL VARIABILITY AND FISH KILLS

CHAPTER 8

REMEDIATION AND MANAGEMENT STRATEGIES

ACRONYMS AND ABBREVIATIONS

ANZECC	Australian and New Zealand Environment and Conservation Council
ABS	Australian Bureau of Statistics
APEC	Asia Pacific Economic Cooperation
API	Application Programming Interface
ASS	Acid Sulfate Soils
AASS	Actual Acid Sulfate Soils
ASSPRO	Acid Sulfate Soil Program
ASSAY	Acid Sulfate Soil Newsletter
AGLS	Australian Government Locator Services
AGNPS	Agricultural Nonpoint Pollution Source Model
ANSWERS	Areal Non-point Source Watershed Environmental Response Simulation
ASDI	Australian Spatial Data Infrastructure
AUSLIG	Australian Survey and Land Information Group
ANU	Australian National University
ANUCLIM	ANU CLIMate
ANUDEM	ANU Digital Elevation Model
ANUSPLIN	Derived from Spline
ANZLIC	Australian and New Zealand Land Information Council
AHD	Australian Height Datum
ANC	Acid Neutralising Capacity
ASSMAC	Acid Sulfate Soil Management Advisory Committee
CAD	Computer Aided Design
CASSP	Coastal Acid Sulfate Soil Program
CSIRO	Commonwealth Scientific and Industrial Research Organisation
COAG	Council of Australian Governments
CVVEICA	Commission on Visualisation and Virtual Environments of the International Cartography Association
DEM	Digital Elevation Model
DSIR	Department of Science, Industry and Resources
DLWC	Department of Land and Water Conservation
ECMS	Electronic Content Management System
EDSS	Environment Decision Support System
ERDAS	Earth Resources Analysis Support System
ESRI	Environmental Solutions Research International

ENSO	El Niño Southern Oscillation
EUS	Epizootic Ulcerative Syndrome
EPA	Environment Protection Agency
EIS	Environmental Impact Statement
FTP	File Transfer Protocol
GDSS	Geographic Decision Support System
GIS	Geographical Information System
GRASS	Geographic Resources Analysis Support System
GWP	Gross World Product
GUI	Geographic User Interface
HEC	Hydrologic Engineering Center
HTML	Hypertext Markup Language
ICT	Information and Communication Technology
IDNAS	Integrated Drainage Network Analysis System
IMS	Internet Map Server
IP	Internet Protocol
IPCC	International Panel on Climate Change
LEP	Local Environment Plans
LINUX	Named after Linus Torvalds
NASA	National Aeronautics and Space Administration
MDNR	Minnesota Department of Natural Resources
NGA	Non-Government Agency
NHMRC	National Health and Medical Research Council
MLMIC	Minnesota Land Management Information Centre
NPP	Net Primary Production
NPV	Net Present Value
NWPASS	National Working Party on Acid Sulfate Soils
OSDM	Office of Spatial Data Management
PASS	Potential Acid Sulfate Soils
PDO	Pacific Decadal Oscillation
PHP	Hypertext Preprocesser
PVC	Polyvinyl Chloride
RACAC	Resource and Conservation Assessment Council
RIRDC	Rural Industries Research and Development Corporation
SDSS	Spatial Decision Support Systems
SEA	State of Environment Australia

SEPP	State Environment Protection Plans
SMASS	Simulation Model for ASS
SO	Southern Oscillation
SOI	Southern Oscillation Index
SQL	Structured Query Language
STL	Seasonal and Trend decomposition using Loess
TCP	Transmission Control Protocol
TEV	Total Economic Value
TIFF	Tagged Image File Format
TIN	Triangular Irregular Network
TNT	Trusted Network Technologies
TSC	Tweed Shire Council
UMN	University of Minnesota
UNIX	UNiplexed Information and Computing System (originally abbreviated as UNICS)
UNSO	United Nations
UTM	Universal Transverse Mercator System
XML	Extensible Markup Language

LIST OF FIGURES

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 6

CHAPTER 7

CHAPTER 9

LIST OF TABLES

CHAPTER 11

LIST OF TABLES

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

TITLE PAGE IMAGES

Chapter 1. The ocean-land fringe, NSW Far North Coast.

Chapter 2. Scanning-Electron Micrograph of a Pyrite Framboid. Photo by Dr Richard Bush, Southern Cross University.

Chapter 3. McLeods Creek Drain, Tweed Catchment.

Chapter 4. An aerial view of the Tweed Catchment and a digital representation.

Chapter 5. Cudgen Lake. Photo by Phil Johnston.

Chapter 6. McLeods Creek flood, 2001. Photo provided by Mark Tunks, Tweed Shire Council

Chapter 7. A Fish Kill in the Cudgen Catchment.

Chapter 8. Blacks Drain, Photo by Phil Johnston.

Chapter 9. An Anthropogenic appreciation of ecosystem services, Cape Byron.

Chapter 10. Virotec 5th International Acid Sulfate Soils Conference, Tweed Heads, Australia.

Chapter 11. Acid sulfate soil characterised by the yellow mineral Jarosite.

CHAPTER 1
Introduction

Chapter 1. Introduction

The world's coastal zone is immensely valuable and is also greatly valued by communities. Costanza *et al.* (1997) estimated the annual value of the world's coastal goods and ecosystem services to be $US24 trillion, compared to an annual global Gross Domestic Product of $US18 trillion. However, the coastal zone is under great threat (Kremer and Crossland, 2002). This thesis examines an integrated approach to coastal zone management in a study catchment in eastern Australia.

1.1 The Coastal Zone

Continued population growth has resulted in an increased disturbance of the land and its natural resources. Coastal zones around the world have come under mounting environmental pressure from farming and urbanisation. Although the coastal regions of the world account for only 12% of the global surface (Barthel *et al.*, 1999), more than 50% of the world's population live within 60-100 Km of the coastline (UNEP, 1995). In Australia, this figure is much higher with around 83 % of the population living within 60 km of the coastal fringe (ABS, 1996). There are numerous definitions that define where the coastal zone begins and ends, however, there is no precise definition for the coastal zone. According to the OECD the size of the coastal zone is proportional to the characteristics of the problem at hand and the management strategy used to address the problem (Kremer and Crossland, 2002). The Land-Ocean in the Coastal Zone (LOICZ), uses a standardised approach based on spatial interpretation which defines the coastal zone as the area comprising the terrestrial and continental shelf that is within the elevation range of ± 200 m (Pernetta and Milliman, 1995). Generally, it is defined as the zone that encapsulates river catchments, estuaries, beaches and other regions including the continental shelf (Kremer and Crossland, 2002).

In terms of agricultural and fisheries production, coastal regions are among the most productive in the world (Costanza *et al.,* 1998). Tourism has also benefited enormously from the use of these regions and its resources (WTTC, 1999). However, the value derived from coastal regions is more commonly measured by economic performance of coastal industries rather than the environmental benefits such as water quality and biodiversity, that they provide.

1.2 Economic and Environmental Benefits of Australia's Coastal Zones.

Australia's coastal region is used by a broad range of interest groups. Conflict between groups is common due to the diverse range of views and priorities related to land and water issues both at the local and regional scale. The relatively young, fertile soils, warmer temperatures and higher rainfall of the coastal zone makes this region attractive for agriculture. In eastern Australia, cattle, sugar cane and dairy farming have been carried out for 150 years. The sugar industry alone contributed around $AUD 565 million to the Australian economy during 2001 (ABS, 2002).

Other enterprises such as the fishing and aquaculture industry are also productive despite the fact that they are more at risk from the impacts of coastal zone development than agriculturally-based industries. Despite this, the aquaculture industry is one of Australia's fastest growing industries with farmgate production for 1999-2000 around $AUD 678 million compared with only $AUD 188 million for 1989-1990 (ABS, 2000). The oyster industry in Australia had a relatively long history of successful pearl and shellfish production. However, the industry has suffered large production losses in some coastal regions. This has been primarily attributed to the inability of governments to protect estuarine areas (White, 2001a). Over 65% of commercial fish species in Australia spend part of their life cycle in estuaries. The seafood industry is the fourth largest primary producing industry in Australia with the gross value of production for 2000-2001 estimated at $AUD 746 million (ABARE, 2002).

Large industries, such as the tourism and construction industry, are also users of the coastal zone and its resources. Tourism is one of Australia's largest industries, with coastal and marine tourism contributing more than $AUD 15 billion to the economy (Commonwealth of Australia, 2001). This represents around 4 % of the Gross Domestic Product (DITR, 2002) and a 50% economic contribution to the marine industry sector (Greiner *et al.,* 1997). Although tourism provides economic benefits to local communities, it places more pressure on natural ecosystems due to seasonal fluctuations in population density. Coastal regions experience large increases in population growth during peak holiday periods. In addition, there has been an internal migration of Australians to coastal areas, particularly South West Queensland and Northern NSW. It has been estimated that the population growth for the NSW north coast will exceed 700,000 by the year 2021 (Commonwealth of Australia, 1996).

1.3 Anthropogenic Impacts on Coastal Zones

A combination of both human and biophysical pressures is responsible for shaping the state of the coastal zone (figure 1.1). The so called 'drivers and pressures' imposed on coastal regions have predominantly developed as a consequence of human activity and behaviour. Human activity now has a much greater impact on the environment than at any other time during the Earth's history. So great have been the changes that it has been acknowledged that humans are now living in a new geological epoch known as the "Anthropocene" (IGBP, 2001).

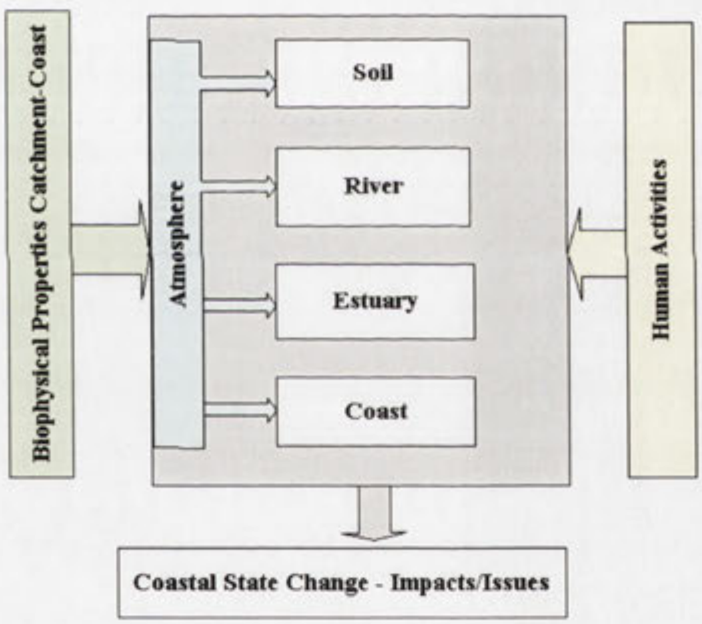


Figure 1.1 Drivers and pressures of the coastal zone [Source: Kremer and Crossland, 2002, p8].

In response to the increase in demand, coastal zone developers have seldom taken into account the impact of development on ecosystems. These anthropogenic affects have led to a wide range of environmental problems including a deterioration in water quality through increased pollution and nutrient contamination (De Roo, 1998). Poor water quality has led to the eutrophication and destruction of estuarine and marine habitats. Although efforts have been made to minimise the inputs of the 'classical' pollutants (ie sewage and nutrients) through the use of improved environmental technologies and standards (Heath and Bergman, 1997; Harries *et al.*, 1998), little has been done to effectively address the "physical changes" to the landscape (ie drainage, floodgates and diversions) which impact on catchment hydrology and groundwater systems (Kremer and Crossland, 2002). Furthermore, the impacts associated with future climate change, such as rising sea levels and changes in rainfall distribution and intensity, may only exacerbate current problems (IPCC, 1990).

The Drivers, Pressures, State, Impacts, Response (DPSIR) Model, has been widely used in coastal management. This recognises the relationship between resource use and its impact on the state or condition of the environment (Turner *et al.*,1998). An adaptation of this model has been proposed by the Australian Commonwealth Government and is shown in figure 1.2 (Commonwealth of Australia, 1996). The DPSIR Model also implies that the impacts of human activities are driven by management decisions and policy response and that communication and dialogue between relevant stakeholders is an integral part of the DPSIR cycle.

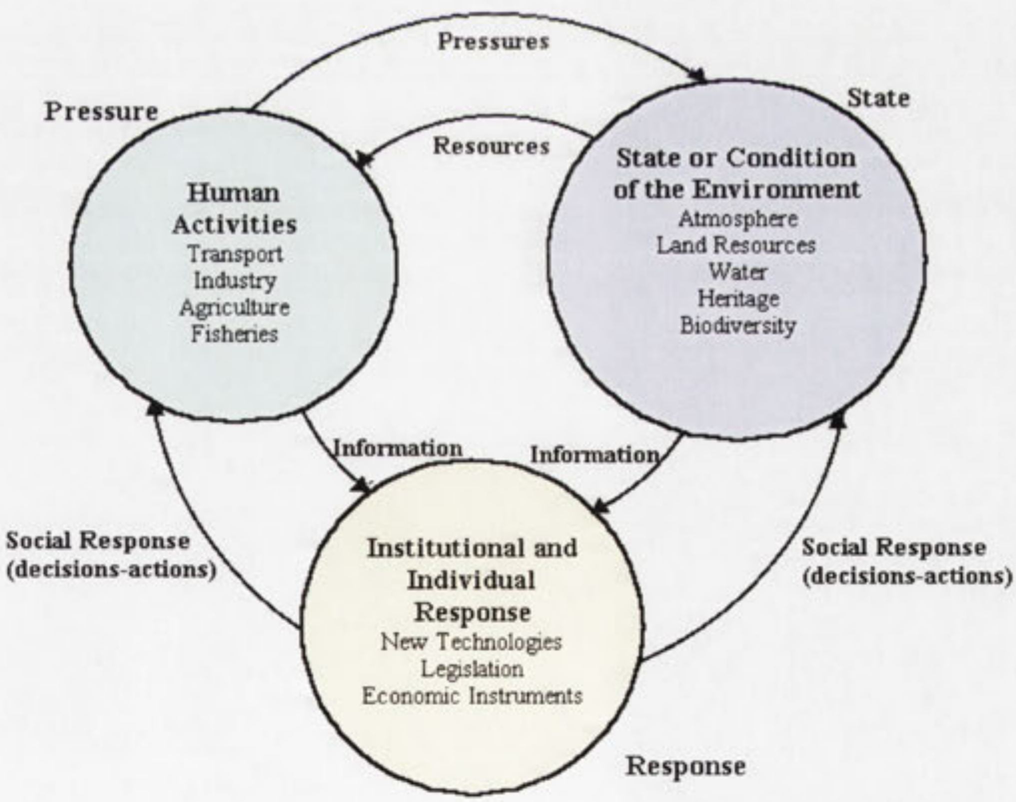


Figure 1.2 An adaptation of the DPSIR Model for the Australian situation [Source: Commonwealth of Australia,1996, p1-7].

1.4 Integrated Systems for the Management of Coastal Catchments

Despite an increase in the awareness of environmental problems resulting from changes in coastal landscapes, there is still a lack of understanding of the complex interactions between the natural environment (such as climate) and changes associated with human activities at all scales of measurement. The coastal zone is an heterogenous system that is not a static system but is in a continuous state of change which can be measured on daily (rainfall and streamflow), seasonal (climatic variability), annual (rainfall), decadal (Pacific Decadal Oscillation) to glacial and interglacial time periods (Kremer and Crossland, 2002). Improvements need to be made to the integration of interdisciplinary work, (such as monitoring and modelling work, scientific and institutional and policy activities), with a much greater emphasis placed on developing new methodologies that will improve the understanding and detection of environmental change and resilience over time (Crooks and Turner, 1999; Harremoes and Turner, 2001).

There is an increasingly recognised need for an integrated approach to the management of coastal zones that encompass both natural as well as the socio-economic factors and which treats all the natural process (ie rainfall, evaporation, streamflow) within coastal catchments as an integrated system. According to Kremer and Crossland, (2002), p3:

" the scientific community is challenged to provide information for solutions that require improved integrated approaches of the natural and socio-economic disciplines and that consider the whole water cascade from river catchments to the continental margins as a connected system"

The wide range of views, objectives and the increasing conflicts between users of coastal zones has meant that governments have attempted to respond to their different expectations. These responses have created a demand for more effective and better communication strategies. With increasing environmental problems come greater societal pressures on the scientific community to provide clear and accessible information. The widely held view is that science communication has been lax and poor at delivering clear and concise information to the public (Kremer and Crossland, 2002).

1.5 Acid Sulfate Soils and the Coastal Zone

There are many land use issues that are of concern in coastal areas. Acid sulfate soils (soils containing iron sulfide minerals that when oxidised, produce acidic ground and surface waters) exemplify the range of climate, land use, water quality and social conflict issues. There are around one million square kilometres of acid sulfate soils in the world's coastal areas, with large areas of acid sulfate soils found throughout Asia, Africa and Latin America (van Breeman, 1982). It is estimated that in Australia there are around 40,000 square kilometres of coastal acid sulfate soils (Lin and Melville, 1992). Figure 1.3 shows the extent of coastal acid sulfate soils in Australia. This represents about the same area affected by dryland salinity (White and Melville, 1996). In comparison to dryland salinity, these soils may constitute a greater problem to rural producers. Around 25% of farmers report problems relating to soil acidity compared to 20% for dryland salinity (Mues *et al.,* 1998).

When acid sulfate soils are exposed to oxidising conditions through human activities, such as drainage and excavàtion, large quantities of sulfuric acid and other acidic products are generated within the soil profile. While climatic conditions in lowlands are highly favourable for crop and pasture production, they also experience regular floods and droughts. Flooding or heavy rainfall may result in the subsequent export of acidic groundwater from the soil into streams and aquatic ecosystems (Wilson, 1995; Sammut *et al.*,1996; White *et al.*,1997). Over the last 100 years, entire regions of coastal lowlands in Australia and elsewhere have been drained and cleared of native vegetation for agricultural production and urban development (White *et al.*, 1999a).

The acidic drainage from these soils represents a threat to the coastal environments. The impacts include fish kills (Callinan *et al.*, 1993; Green 1993; Sammut *et al.*, 1996), corrosion of engineering structures (White and Melville, 1996), reduced plant growth and productivity (Dent, 1986) as well as adverse changes in aquatic ecosystems and their biomass (Cheers, 1992; Sammut *et al.,* 1996).

1.6 Acid Sulfate Soils in New South Wales

There are over 600,000 hectares of acid sulfate soils in New South Wales (NSW) of which approximately 200,000 hectares have been disturbed as a result of human settlement. It has been estimated that there is about 10 million tonnes of stored sulfuric acid in these soils and approximately 50,000 tonnes is discharged into streams and rivers each year (ASSMAC, 1999a). The environmental costs resulting from the acidic drainage from these soils will continue to accrue for many decades - if not centuries to come - unless catchment managers and land owners are prepared to adopt sustainable land management practices.

Figure 1.3 Distribution of potential acid sulfate soils in Australia (Adapted from White and Melville, 1993).

A study of the awareness of land holders in coastal lowlands of NSW of the impacts of acid sulfate soils (Woodhead, 1999) revealed that only 45% of farmers surveyed knew whether they had acid sulfate soils on their properties. Only 20% of farmers surveyed knew the pH of their drainage water. This was despite five years of an intensive communication campaign on the impacts of acid sulfate soils. This highlights the need for a more effective way of presenting and communicating information to land holders.

1.7 Objectives and Scope of this Thesis

Site specific field trials generally ignore the broader implications of climate and land management decisions at the catchment scale. To date, there is no general, systematic way of determining the impact of changes in land and water management strategies on the export of acidity in coastal floodplains and making that information accessible to land holders. Instead, we rely on expensive, local site specific trials, which seldom take into account the surrounding catchment hydrology and the inherent spatial and temporal variability of climate. It is difficult to separate the anthropogenic effects on water quality from the influences of climate variability. Thus, it is difficult to generalise from one catchment to another. This thesis examines these issues and attempts to develop an integrated and systematic approach to the management of coastal catchments containing acid sulfate soils by using a Geographic Information System (GIS) modelling approach to water and land management at the catchment scale.

1.7.1 Overall Aim of this Thesis

The overall aim of this work is to develop a readily-accessible information system on coastal acid sulfate soils that incorporates climate, soil and catchment characteristics and which can be used by land holders to assess the outcomes of changes in acid export, resulting from management interventions at the broad scale catchment level. More importantly, this research uses an integrated approach to the management of coastal acid sulfate soils and takes into account not only the broader impacts of climate and land management decisions, but also the economic costs. Here the system is developed for a northern NSW catchment but the methodology is applicable and transferable to other NSW coastal catchments. An overview of the project and its objectives is summarised in figure 1.4.

1.7.2 Specific Objectives

The specific objectives for the study catchment are to:

(1) Develop a GIS for the Tweed and Cudgen Catchments that includes soil, land use, drainage and elevation data.

(2) Construct a GIS-based hydrological model for coastal catchments by using a water balance approach to simulate stream flow based on spatially-variable rainfall.

(3) Examine trends in long-term climate variability in the Tweed.

(4) Use the hydrological model to assess the impact of drainage and climate variability on acidification of downstream water bodies and develop an indicator for predicting fish kill events from climate records.

(5) Examine a range of remediation strategies and their implications for policy makers and land managers.

(6) Analyse and assess the cost of these remediation strategies and compare their cost with the cost of ecosystem services for the Cudgen Catchment.

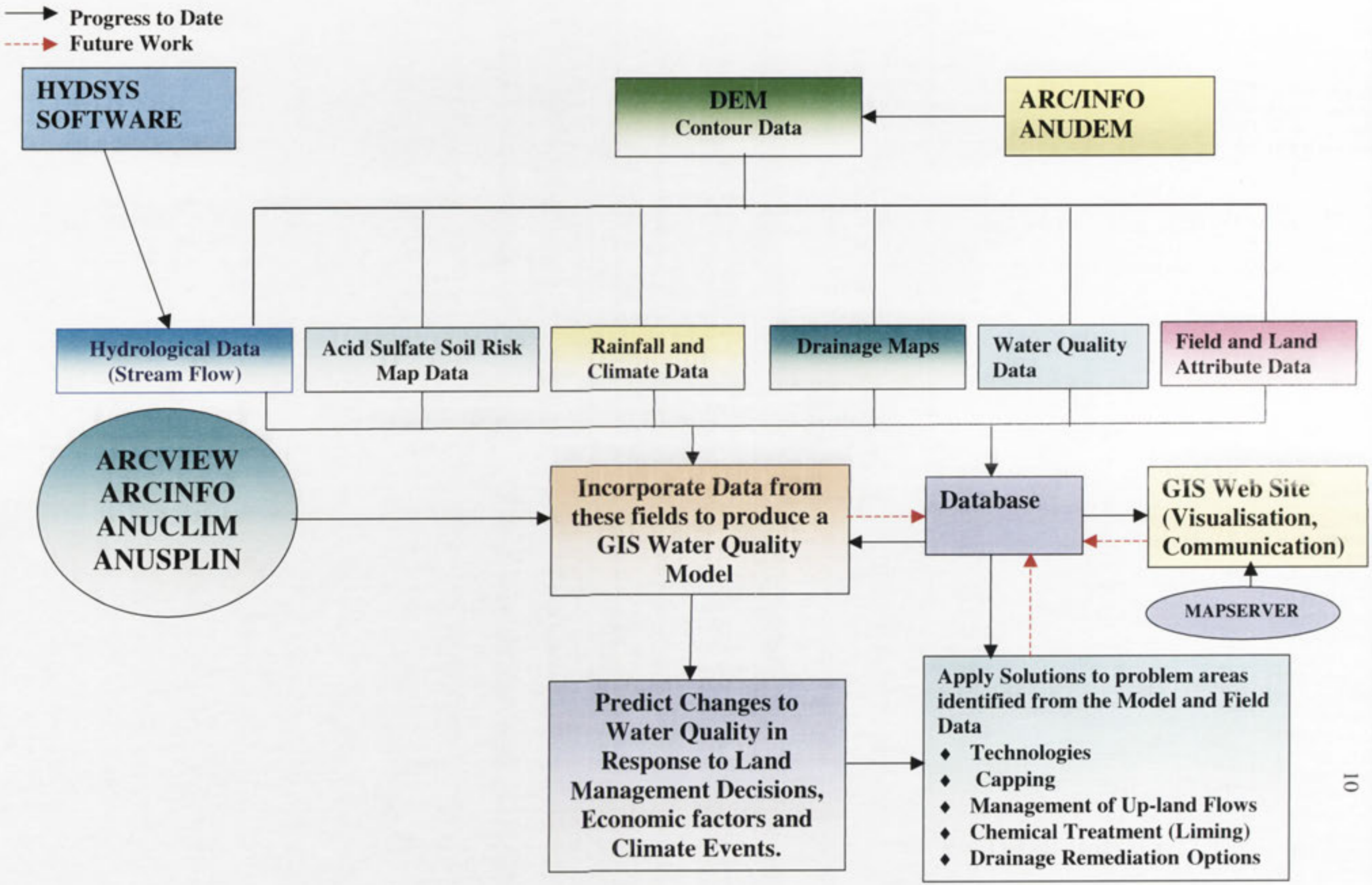
(7) Develop a communication framework for acid sulfate soil management including the development of a low cost on-line Geographic Decision Support System for land use managers and others.

1.7.3 Outline of Thesis

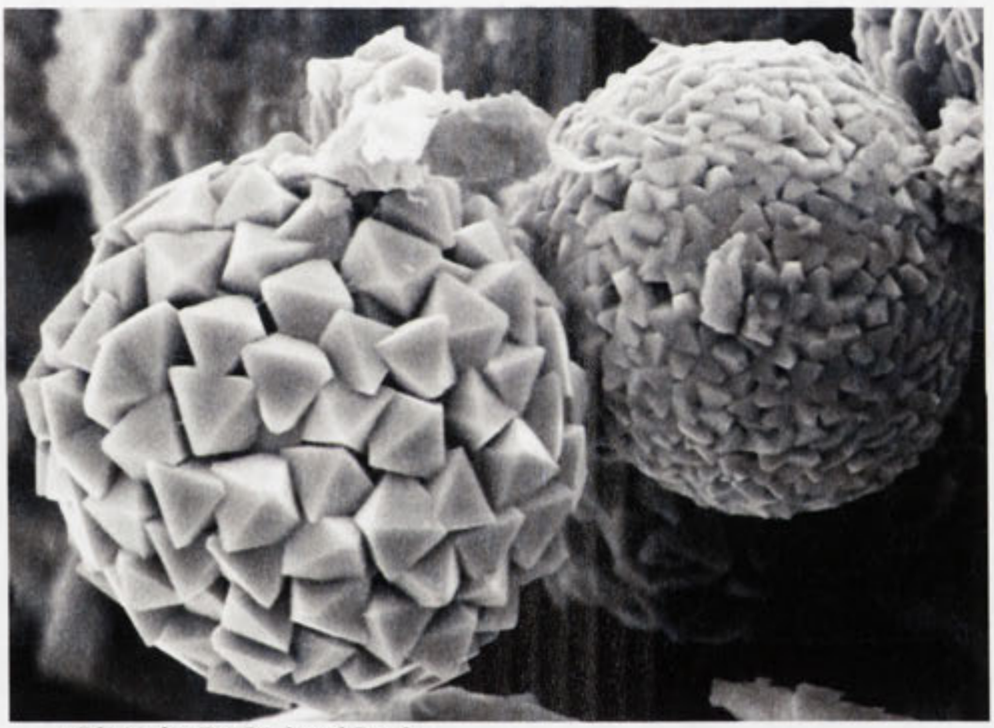
The thesis is divided into eleven chapters. These chapters are:

Chapter 1 Introduction.
Chapter 2 Acid Sulfate Soils; A Synopsis
Chapter 3 Integrated Hydrological-Water Quality GIS Models
Chapter 4 Development of a GIS-Hydrological Model for the Tweed Catchment.
Chapter 5 The Cudgen Catchment: A Baseline Study.
Chapter 6 Trends in Rainfall Variability in the Tweed.
Chapter 7 Rainfall Variability and Fish Kills.
Chapter 8 Remediation and Management Strategies
Chapter 9 Cost of Remediation and Ecosystem Services for the Cudgen Catchment
Chapter 10 Communication Strategies for Achieving Better Management of Acid Sulfate Soils
Chapter 11 Final Discussion, Conclusion and Future Directions

Figure 1.4 Integrated GIS Water Quality Model



CHAPTER 2
Acid Sulfate Soils: A Synopsis



(Photo by Dr Richard Bush)

Chapter 2. Acid Sulfate Soils: A Synopsis

2.1 Introduction

Continued population growth and density has placed unsustainable pressure on Australia's coastal ecosystems (Commonwealth of Australia, 2001). One of the major threats to estuarine ecosystems is from acidification (Commonwealth of Australia, 2001). The periodic acidification of many coastal streams in Australia has been attributed to acid sulfate soils. This process occurs when pyrite (cubic FeS_2) in the sediments oxidises to produce sulfuric acid. Oxidation occurs when acid sulfate soils become exposed to the air, such as during periods of prolonged drought or when the watertable is lowered through drainage for urban development or agricultural production (Dent, 1986).

The impact of acid exported from these soils on agriculture, human health and aquatic ecosystems is complex and poorly understood. The resulting environmental impacts of acid runoff include the destruction of fish habitats as well as the loss of aquatic biodiversity. From an economic perspective, it has been estimated that more than $AUD 4 million worth of fish, prawns, and oysters are lost annually as a result of aquatic acidification (White, 2001a). This literature review provides an overview of acid sulfate soils in Australia and their impact on the environment.

2.1.1 Identification and Classification of Acid Sulfate Soils

The identification and classification of acid sulfate soils has been a contentious issue (see van Breemen, 1982; Fanning and Witty, 1993) with recognition given to the fact that there was a need to revise the 1990 Keys to Soil Taxonomy (Soil Survey Staff, 1990) (van Breemen, 1982; Pons, 1988; Pons *et al.*,1989; Fanning and Witty, 1993). Numerous reports have identified the main problems associated with classifying pyritic soils. For example, various researchers have reported the presence of acid sulfate soils in which jarosite was absent (van Mensvoort and Le Quang Tri, 1988; Wilson, 1995). Others have reported the discovery of soils containing sulfidic material but have been unable to adequately categorise these soils using current soil classification systems (Fitzpatrick *et al.*, 1993).

Van Breemen (1982) and Fanning and Witty (1993) suggested that the present definition for acid sulfate soils was too ambiguous with respect to the colour criteria for jarosite mottles. Fanning and Witty (1993) had proposed that the old definition in the Soil Survey Staff (1990) should be removed and replaced with a new definition which disregards any reference to colour.

During the 4th International symposium on acid sulfate soils, it was agreed that the current definition required revision and that a new definition be included in Keys to Soil Taxonomy (Soils Survey Staff, 1994).

The new definition states:

> *The sulfuric (L.sulfur) horizon is 15 cm or more thick and is composed of either mineral or organic material that has a pH< 3.5 (1:1 by weight in water, or in a minimum of water to permit measurement) under field conditions and evidence that the low pH is caused by sulfuric acid. The evidence is one or more of the following: a) jarosite mottles, b) immediately subjacent sulfidic materials, or c) 0.05 percent or more water soluble sulphate.*

Soils containing unoxidised sulfides, but which have the potential to cause acidification when oxidised, are referred to as sulfidic or Potential Acid Sulfate Soils (PASS) (Dent, 1986), whereas, soils which are in the process of oxidising are called sulfuric or Actual Acid Sulfate Soils (AASS). Potential Acid Sulfate Soils have the potential for acidification if the soil is oxidised. Both AASS and PASS are generally referred to collectively as Acid Sulfate Soils (ASS). Acid sulfate soils are also often referred to in the literature as pyritic sediments or sulfidic/ sulfuric sediments or soils.

2.1.2 Formation and Accumulation of Iron Sulfides in Sediments

Iron pyrite (cubic FeS_2) formation can only occur in certain environments and under specific conditions. Environments which favour their formation include mangrove swamps (Lin and Melville, 1992), salt marshes and coastal lakes, where there is terrigenous material present (Berner, 1984; Pons *et al.*, 1982). There are, however, regional differences noted between acid sulfate soil profiles (Diemont *et al.*, 1993), depending on the environmental conditions. In eastern Australia, the top of the sulfidic layer is about 1 metre above the current mean sea level, which is approximately equal to 1 metre above the Australian Height Datum (AHD) (White and Melville, 1996).

A large area of Australia's coastal regions contain iron sulfide sediments which were mostly deposited during the Holocene sea level rise period, over approximately the last 10,000 years (Dent, 1986). Although these recent sulfidic sediments are primarily found in coastal marine environments, they have also been discovered in regions far removed from mangrove swamps and other estuarine environments, including regions of the Murray-Darling Basin (Sullivan *et al.,*2002). This suggests that these areas must have had conditions similar to those currently observed in estuarine and mangrove environments.

An examination of the Earth's climatic events over the last 6500 years provides a clearer insight into the past processes that favoured the formation of sulfidic sediments. A rise in the sea level resulting from the last glacial maximum, led to the flooding of coastal rivers valleys and estuaries. This marine incursion event, which concluded around 6,500 years ago (Thom and Chappell, 1975), allowed sulfate containing sea water, to invade near-shore regions and led to the rapid expansion of mangrove habitats (Woodroffe and Chappell, 1991). The sea level rise (over 100 metres) and its gradual stabilisation led to the burial of vegetation by sediments and subsequently led to the formation of PASS. The formation of sulfide sediments still occurs in marine environments such as mangrove and tea tree swamps (Lin and Melville, 1992), and coastal marine bottom sediments (Berner, 1984). The continued formation of these sulfidic sediments is an integral part of the sulfur cycle. It is estimated that in Australia there is around 30,000 square km of ASS (White and Melville, 1996) containing approximately one billion tonnes of pyrite (Lin and Melville, 1992).

The conditions required for the formation of reduced iron sulfide species in sediments are:

(1) A source of dissolved sulfate

(2) The presence of labile organic matter

(3) An adequate supply of iron

(4) Predominantly anaerobic conditions

(5) Tidal flushing to remove reaction products

These conditions are most commonly found in coastal regions where there are adequate supplies of dissolved sulfate in brackish waters, large deposits of labile organic matter and generally anaerobic iron-rich sediments. The formation of iron sulfides occur when sulfate-reducing bacteria, such as *Desulfovibrio desulfuricans* reduces sulfate to hydrogen sulfide in the presence of organic matter. The bacterial reduction of sulfate takes place via a complex series of reactions, often involving the utilisation of biopolymeric organic compounds (Berner, 1984).

The organic matter (represented as CH_2O in equation 2.1) is utilised by the bacteria as an energy source (Berner, 1984), while SO_4^{2-} acts as the electron sink for bacterial respiration. In the process, SO_4^{2-} is reduced to sulfide (Goldhaber and Kaplan, 1974; Goldhaber and Kaplan, 1982; Berner, 1984).

The equation can be expressed as:

$$½\,\mathrm{SO_4^{2-}} + CH_2O \rightarrow ½\,\mathrm{H_2S} + \mathrm{HCO_3^-} + \mathrm{H_2O} \qquad 2.1$$

The sulfate reducing bacteria responsible for this process live under anaerobic conditions found in estuarine or marine sediments (Vaughan and Lennie, 1991). Aerobic bacteria, which live near the sediment-water interface, also use the organic matter as an energy source. Aerobic bacteria take up dissolved oxygen and release carbon dioxide. The removal of oxygen and the subsequent production of CO_2 effectively ensures that anaerobic conditions are maintained within the lower sediments essential for sulfate reduction by anaerobic bacteria (Berner, 1984).

The soluble form of the sulfide, H_2S produced in equation 2.1 can react with Fe^{2+} liberated under anaerobic conditions (Berner, 1984; Raiswell, 1993) to produce metastable iron monosulfides. Examples of iron sulfides formed from this process include ferrous sulfide (FeS) and greigite (cubic Fe_3S_4) (Goldhaber and Kaplan, 1982; van Breemen, 1988).

The reaction between Fe^{2+} and H_2S can be summarised as:

$$Fe^{2+} + S^{2-} \rightarrow FeS \qquad 2.2$$

The supply of dissolved sulfide in reaction 2.2 is continuously renewed by the tidal cycle via equation 2.1, which not only allows for the deposition of new sulfide sediments but also removes soluble by-products such as soluble bicarbonate (Dent, 1986). Recent work in Australia has demonstrated the importance of the formation of iron monosulfides (Sullivan and Bush, 2002).

Although a small percentage of the monosulfide (FeS) minerals produced in equation 2.2 precipitates, most are converted to pyrite (FeS_2) by a reaction involving elemental sulfur and the metastable iron sulfide FeS.

The reaction can be summarised as:

$$FeS + S \rightarrow FeS_2 \qquad 2.3$$

When viewed under a scanning electron microscope, pyrite can appear as framboids of small crystals measuring around 30 μm in diameter (Dent, 1986). It has been shown that in marine marsh sediments, pyrite can still be produced without the formation of the monosulfide intermediate from the reaction involving detrital iron and H_2S (Howarth, 1979). The ratio of FeS_2/FeS can differ depending on the type of marine or estuarine environment in which they were formed (Berner *et al.,* 1979). The incomplete conversion of FeS to pyrite is also possible if the rate of sulfate reduction occurs too quickly and there is a rapid depletion of both sulfate and H_2S (Berner *et al.*, 1979). This situation takes place when there is a rapid rate of sediment deposition in conjunction with the burial of large amounts of highly reactive organic matter (Goldhaber and Kaplan, 1975; Toth and Lerman, 1977; Berner, 1978).

Various authors have discussed the role of organic matter, sulfur and iron on the rate of pyrite formation (Kaplan and Rittenberg, 1964; Berner *et al.,* 1979; Pons *et al.*,1982; Berner, 1984; Lin and Melville, 1992). The rate of sulfate reduction is dependent to a large extent, on the reactivity of the organic matter deposited within the sediments (Kaplan and Rittenberg, 1964; Pons *et al.*,1982; Berner, 1984).

Apart from the quality of organic matter, the availability of iron as well as the reactivity of the iron minerals within the sediment, is also a limiting factor determining the rate and extent of pyrite formation (Berner, 1984; Giblin, 1988). Sediments containing $CaCO_3$, derived from the skeletal remains of marine organisms, usually contain low levels of available iron and hence low levels of pyrite are produced, even when there is an abundance of H_2S and organic matter (Berner, 1972; Berner, 1984; Gibson, 1985). The opposite is true for terrigenous marine sediments in which there is usually an abundance of reactive iron species (Berner, 1984). Another factor that affects sulfide reduction rates includes the rate of sediment deposition. A rapid rate of sediment deposition ensures that organic matter will not quickly decompose through long-term exposure to air (Berner, 1984).

The rate of sulfate reduction and the subsequent rate at which pyrite is produced can vary from less than one day (Howarth 1997), to up to 10^6 years (Goldhaber and Kaplan, 1982; Pons and van Breemen, 1982) depending on the environmental factors previously discussed.

The concentration of pyrite in Australian sediments can vary from 0.01 up to 10% (w/w) (White *et al.*, 1997) depending on the region and can occur in a range of soil types including unconsolidated muds and coarse sediments such as sand and gravel. Unconsolidated Holocene sulfidic deposits have been discovered with a thickness of more than 10 metres (Willett *et al.*, 1992; Wilson, 1995). Furthermore, the concentration of sulfides in sediments formed in warmer regions appears higher than in those formed in colder regions (White *et al.*, 1997).

2.1.3 Oxidation of Sulfidic Sediments

Sulfidic sediments pose no threat to the environment provided they are not exposed to oxidising conditions. In other words, as long as the sulfides are maintained below the watertable and remain in the reduced state, there are no problems. However, serious problems can occur during extended periods of drought or when sulfidic sediments are physically exposed to the air, such as following drainage, excavation or dredging (White *et al.*,1997). Oxidation of pyrite occurs during these events, with the process taking place at a faster rate, when the pH drops to below 4 (Nordstrom, 1982). The drop in pH from 7 to 4 is purely a chemical process driven by oxygen, however, once the pH drops to below 4 the oxidation process is catalyzed by micro-organisms and is temperature dependent.

The oxidation of pyrite involves a series of reaction steps (Willett *et al.,*1992), which converts solid pyrite to dissolved iron and sulfate (Nordstrom, 1982). The equation can be written as:

$$FeS_{2(s)} + \tfrac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad 2.4$$

The iron (II) in equation (2.4) can then undergo further oxidation to produce iron III, resulting in the production of more acid. The oxidation of iron II results in the formation of typical red-brown ferrihydrite (FeOOH) flocs often associated with waters containing iron compounds and can be transported via the drainage networks into streams and coastal lakes (Nguyen and Wilander, 1995).

The formation of these flocs is represented by:

$$Fe^{2+} + \tfrac{1}{4}O_2 + \tfrac{3}{2}H_2O \longrightarrow FeOOH + H^+ \qquad 2.5$$

Ferric oxyhydroxide is precipitated at pH greater than 4, whereas, at pH less than 4, the solubility of Fe (III) increases (Nordstrom, 1982; van Breemen, 1993) and Fe (III) may remain in solution. The conversion of Fe (II) to Fe (III) results in the maintenance of acidic conditions often at a distance downstream from the source of sulfides. Under these highly acidic conditions, Fe (III) oxidizes pyrite and, as a result, Fe (III) becomes reduced. Therefore, provided the soils remain acidic, the oxidation of pyrite can occur even in the absence of dissolved oxygen. This factor has serious implications in development of suitable remediation strategies for the treatment of acid discharge. For example, the re-flooding of oxidised acid sulfate soil floodplains to control acidification may not be a satisfactory solution (White *et al.,* 1997).

The oxidation rate of pyrite is faster when Fe (III) is the oxidising agent than oxygen alone (Garrels and Thompson, 1960). This self perpetuating process is catalysed by the autotrophic micro-organism *Thiobacillus ferrooxidans* which is often abundant in acid sulfate soils (Nguyen and Phan Lieu, 1993). It is now widely accepted that once the pH drops below 4, the reduction of Fe (II) to Fe (III) by *T. ferrooxidans* is the main process responsible for the oxidation of ASS with considerable quantities of Fe III often produced (Bloomfield and Coulter, 1973). Under acidic conditions, the production of Fe III *by T.ferrooxidans*, takes place according to the following equation:

$$2FeSO_4 + \tfrac{1}{2}O_2 + H_2SO_4 \longrightarrow Fe_2(SO_4)_3 + H_2O \qquad 2.6$$

Reaction (2.6) can still proceed without *T.ferrooxidans*, however at a much slower rate.

The oxidation of pyrite then takes place under acidic conditions by the following two reactions:

$$FeS_2 + Fe_2(SO_4)_3 \longrightarrow 3FeSO_4 + 2S \qquad 2.7$$

$$2S + 6Fe_2(SO_4)_3 + 8H_2O \longrightarrow 12FeSO_4 + 8H_2SO_4 \qquad 2.8$$

Because these reactions take place in solution, the above two equations can be combined as:

$$FeS_{2(s)} + 14Fe^{3+}{}_{(aq)} + 8H_2O_{(l)} \longrightarrow 15Fe^{2+} + 16H^+ + 2SO_4^{2-} \qquad 2.9$$

The oxidation of pyrite by Fe (III) (equation 2.7) occurs at a faster rate than the oxidation of Fe (II) to Fe (III) (equation 2.6). Because of the difference in the rates of these two reactions, Fe (III) is reduced at a faster rate than the conversion of Fe (II) to Fe (III) by oxygen and the reaction eventually comes to a stop (Nordstrom, 1982). However, this difference is not crucial when it is considered that *T.ferrooxidans* catalyses the oxidation of Fe (II) to Fe (III) five orders of magnitude faster compared to the same reaction with oxygen alone (Lacey and Lawson, 1970; Singer and Stumm, 1970).

Despite this, the oxidation of pyrite resulting from the accelerated production of Fe (III) by *T.ferrooxidans*, has only been shown in the laboratory (Pesic *et al.*, 1989) in which oxygen was not a limiting factor. Conditions in the field vary far more considerably than those that can be provided *in situ*. With this in mind, it is possible that oxygen may be the rate limiting factor, particularly in waterlogged soils where the diffusion of oxygen through water is much slower than through soil air (Eriksson, 1993). Despite the fact that *T.ferrooxidans* accelerates this oxidation process, oxygen is still required for this reaction (equation 2.6) to proceed. According to Dent (1986) and others (Dent and Raiswell, 1982; van Breemen, 1993) the availability of oxygen is the rate determining step for the production of acid from ASS. However, it has also been said that soil acidity cannot be reversed through maintaining a high watertable or through re-flooding of oxidised ASS landscapes. Provided the soil remains acidic, pyrite oxidation by Fe (III) can still take place even in the absence of dissolved oxygen (White *et al.*,1997). In regions where drainage has taken place, there exists a vast store of acidity in the soil profile which can leach out for 100 years or more (White *et al.*, 1997)

The Iron (II) formed from pyrite oxidation can be exported by surface water flow from their point of origin to other regions in the catchment (Nguyen and Wilander, 1995). This has serious implications in regions not normally associated with ASS. The flocs of ferrihydrite are indicative of sulfide oxidation that has occurred upstream and their formation normally results in the depletion of available dissolved oxygen in the river system. In addition, the aquatic vegetation living beneath the water surface often become smothered by these flocs, thus limiting the availability of light required for photosynthesis (Sammut *et al.*, 1994).

The impact of pyrite oxidation on acid export, depends on the capacity of the surrounding environment to neutralise the oxidation products of pyrite. For example, sediments containing considerable amounts of clay minerals have a greater ability to neutralise acid through ion exchange processes which take place in the soil profile (see Pons *et al.*, 1982; van Breeman, 1982). The capacity of the soil to neutralise the acid produced from the oxidation of pyrite, is defined as the acid neutralisation capacity of the soil (ANC) (ASSMAC, 1996).

2.1.4 Production of Sulfur Dioxide from ASS

The liberation of SO_2 from ASS was first proposed by van Breemen (1993), and further examined by Moorse *et al.* (1987). It is well known that the presence of a sulfurous smell, as well as the corrosion of certain metals, often occurs in the atmosphere above ASS landscapes. However, the concomitant rate of SO_2 formation, which accompanies sulfide oxidation, is not known. In order to understand the complexities involved in SO_2 formation and how they relate to sulfide oxidation and the cycling of sulfur, it is necessary to examine the chemistry of the sulfidic-sulfuric soils. By studying the stoichiometry of whole ASS profiles, van Breemen (1993) proposed that a fraction of the acid produced from ASS was leaving the soil as SO_2. A recent study by MacDonald *et al.* (2004) has shown that there are direct emissions of SO_2 from a range of coastal acid sulfate soil landscapes. This research concluded that the flux of SO_2 is closely linked to soil water evaporation.

2.1 Environmental Impacts

2.2.1 Interaction of Acid with the Soil Environment and the Release of Metal Ions and Heavy Metals

The acid soil water solution in oxidised sulfuric sediments reacts with clay minerals to release silica and metal ions such as aluminium, iron, potassium, calcium, magnesium and sodium (van Breemen, 1993). Dissolved monomeric aluminium concentrations in excess of 100 mg/L have been discovered in heavily acidified (pH 1.6) drainage waters (White *et al.,* 1997). ANZECC (1992) guidelines recommend that aluminium concentrations should not exceed 0.005 mg/L at pH less than 6 for freshwater (Anon, 1992).

The release of heavy metals Zn, Cd, Cu, Ni, Mn, Cr, Pb, As and Co from clay sediments can also occur as a result of acidification (Satawathananont, 1986; Fanning *et al.,*1988; van Breemen, 1993). Heavy metals are released from estuarine sediments at pH less than 4, whereas at around pH 7 or above, they remain bound to the sediments (White and Melville, 1996). The release of heavy metals depends on the geochemistry of the floodplain sediments (van Breemen, 1993) or where there is contamination by heavy metals associated with mining operations (Taylor *et al.,* 1997) or from stormwater runoff containing pesticides (White and Melville, 1996). Sewage wastewater entering rivers and estuarine waters can also have high levels of heavy metals including cadmium and zinc (White and Melville, 1996). Although the association between dissolved metal ions (especially monomeric aluminium) and fish mortalities has been well documented (Driscoll *et al.,* 1980; Sammut *et al.,* 1993;

Sammut *et al.,* 1996), the extent of heavy metal contamination in the food chain and the associated health risks, are largely unknown.

2.2.2 Effects on Plant Growth

One of the greatest impacts of soil acidification is its affect on plant growth and in severe cases, it often leads to a rapid deterioration in productive agricultural land from acid scalding (White, personal communication, 1999). In some South East Asian countries, such as Indonesia, tidal swampland containing acid sulfate soils have been reclaimed for the cultivation of rice and other crops, including coconut, citrus and rambutan (Kselik *et al.*,1993; Muhrial Sarwant *et al.*,1993). Similar agricultural practices have also been undertaken in Thailand and Vietnam where mangrove wetlands have been cleared and replaced with field crops and fruit crops or rice, however with limited success (van Breemen, 1973 a). However, the large presence of PASS has severely restricted these types of agricultural activities and has, in some instances, led to the development of strict water management practices (Hanhart and Ni, 1993; Tuong, 1993). Alternatively, some farmers have resorted to the cultivation of acid tolerant crops such as sugar cane.

One of the indirect consequences of acidification on plant growth is the resulting change in redox conditions in the soil and its effect on metal solubility. Pyrite oxidation produces soluble sulfates and leached salts from clay minerals. The osmotic effects of these salts inhibits the uptake of water and nutrients by plants and can severely affect the yield, for a majority of crops, when the soil water electrical conductivity range falls between 1.5 to 7m Sdm $^{-1}$ (Dent, 1986). The formation and accumulation of H^+, Fe^{2+} and in particular the activity of monomeric Al species can have an adverse impact on plant growth. However, the effects of these ion species on plant growth are complex and usually involve a combination of factors, including the deficiencies of certain trace elements such as magnesium and calcium (Moore and Patrick, 1989a, 1989b; Moore *et al.*, 1990). Furthermore, Auxtero and Shamshuddin (1991) demonstrated that the growth of oil palm (*Elaeis guineensis*) seedlings is affected when there is usually more than one active monomeric Al species present - suggesting that the sum of species is a reliable indicator of Al toxicity.

Despite the effects of acidification on agricultural land there are a few agricultural crops that can tolerate low pH environments. For example, sugar cane, rubber trees, oil palms, bananas and cassava can tolerate moderate acidic conditions. Sugar cane, which is grown extensively on ASS, can withstand low pH concentrations in the range of 3.5 to 5.0. Some native plants such as *Melalueca* sp and some grasses are also adaptable to ASS.

Other impacts on plant growth resulting from ASS drainage may also include exposure to sulfur dioxide. There is a relationship between exposure to SO_2 and acute foliar damage in some crops, including a strong correlation between long-term exposure to low concentrations of sulfur dioxide and reduced crop productivity (Treshow, 1984). The effects of sulfur dioxide derived from ASS on plant growth and crop productivity, have not been determined.

The acidification of lakes and rivers from ASS drainage can also affect aquatic vegetation by altering the light regimes of aquatic environments. Acid waters containing aluminium, for example, can lead to the clarification of turbid waters and the subsequent stratification of rivers and other aquatic habitats (Sammut *et al.*, 1994). In addition, the formation of ferrihydrite floccs can coat the surfaces of aquatic plants thereby limiting their photosynthetic capability. The effects of ASS drainage are not just confined to aquatic plants but are also a major problem to benthic organisms as well (Dent, 1986; Cheers, 1992; Sammut *et al.*, 1994).

2.2.3 Aquatic Impacts from Acidification

The impacts of acidification from ASS on estuarine ecosystems has not received much attention in comparison to the considerable body of work carried out on the impacts of acidification in streams and lakes from acid rain (Driscoll *et al.,* 1980; Sammut *et al.,* 1994).

From an economic perspective, the effects of aquatic acidification on the marine environment is of great significance to the fishing and aquaculture industry (Green, 1993). There are numerous reports linking fish and oyster kills with acidification of aquatic ecosystems (Sammut *et al.*, 1996; Dove, 1997). The ideal pH range for most freshwater biota is between 6.5 and 9.0 (Sammut *et al.*, 1996). The acidification of aquatic ecosystems takes place when sulfuric acid and other acid species are transported from the soil to surface waters. The transportation of acid and other acid species is driven by rainfall. Although rainfall has a positive effect by diluting the acid, it also has a far more devastating impact by distributing and transporting acid, as well as the products of acidification, over considerable distances. Over 90 kilometres of the Richmond River and its tributaries in northern New South Wales were affected by aquatic acidification following a period of major flooding (Sammut *et al.,* 1996). The transportation of acid resulting from a significant rainfall event can have wide implications for aquatic life further downstream.

The toxicological and physiological impacts of acid and acid products on gilled organisms are not fully understood. It would appear that a reduction in pH not only has an adverse effect on the health of fish and other gilled organisms (Wendelaar Bonga and Dederen, 1986), but the presence of dissolved metal ions, particularly aluminium may also contribute to fish kills in waters affected by low pH (Sammut *et al.*, 1993). Increased levels of aluminium have been identified as the main factor responsible for most fish mortalities in marine environments where acidification has occurred (Driscoll *et al.*, 1980). Aluminium interferes with normal gill function in fish and other gilled organisms. Because of the toxicity effects of aluminium on aquatic life in general, it has been recommended that the concentration of aluminium in freshwater should not go above 5.0 μg/L when the pH of the water drops below 6.5 (Anon, 1992). The presence of dissolved metals such as aluminium in estuarine waters, is closely linked to acid discharge events from areas containing acid sulfate soils (Tuong, 1993). If the frequency of these events were to increase then it is likely that aquatic life and the future sustainability of the fishing and aquaculture industries would be seriously affected (Sammut *et al.,* 1996).

Other physiological changes resulting from acidification have been observed in other aquatic organisms other than fish. For example, electron microscopy studies carried out on the Sydney rock oyster *Saccoitrea commercialis* (now classified as *Saccoitrea glomerata)* have revealed an apparent degeneration and dissolution of oyster shells exposed to acidified waters (Dove, 1997; Dove *et al.*, 1999). Toxicological studies have shown that embryonic development in the Sydney rock oyster is also affected by acidification of aquatic environments (Wilson and Hyne, 1997).

Apart from the toxic effects of aluminium and low pH, other factors have also been linked to fish deaths from acid sulfate drainage. For example, Sammut *et al.*1993 have observed fish dying from apparent asphyxiation. It is not certain if this phenomenon is due to low levels of dissolved oxygen resulting from the oxidation of iron II to ferrihydrite or due to the obstruction of the gills from iron or aluminium flocs (Sammut *et al.*, 1993).

A relationship between acidification and aquatic diseases has also been claimed. A recent hypothesis has linked the incidence of QX disease in oysters to increased exposure to acidified waters (Dove *et al.*, 1999). However, further investigation is required to substantiate this claim. It is well documented that the cutaneous fungal disease Epizootic Ulcerative Syndrome (EUS) or 'red spot' disease infects fish that have come into contact with acidified water (Callinan *et al.*, 1993). The oomycete fungus *Aphanomyces* sp, responsible for EUS, causes severe ulcerations by infecting the areas of the skin damaged by the abrasive effects of acid water (Sammut *et al.*, 1993; Callinan *et al.*, 1993; Sammut, 1998). Because EUS causes severe disfigurement to the skin, infected fish caught for food consumption are often rejected. The incidence of EUS is fairly widespread throughout Australia where the disease has resulted in considerable economic loss to the fishing industry (Pearce, 1990; Callinan *et al.,* 1993). EUS is also prevalent in parts of South East Asia (Lilley *et al.*, 1992) and is a major problem to the fishing industry in some of the developing countries in this region.

Despite the serious impact acidification has on aquatic life, there are some species of fish which actively seek out acidified waters. The empire gudgeon *Hypseleotris compressa* for example, can adapt to pH levels as low as 4 (White and Melville, 1996; Easton, 2002).

2.2.4 Physical Impacts

The acidic products from the oxidation of pyrite are not only significant in terms of toxicity to terrestrial plants and aquatic organisms, but also in terms of its impact on the physical environment. The oxidation of pyrite can change the physical properties of the sediments resulting in irreversible shrinkage of the sediment as well as increased permeability (Dent, 1986; White *et al.*,1997). Irreversible shrinkage of the sediments is caused by the removal of water through evaporation, transpiration by plants and through the consolidation of the sediments. These physical changes, which take place over a period of time, are referred to as 'ripening' (van Breemen, 1973 b; Dent, 1986). The drying process has also been implicated in the oxidation of the sediments through the transportation of air via old root channels (White *et al.*,1997). These physical changes impact on the productivity and engineering properties of agricultural land where acid sulfate soils are present.

2.2.5 Impacts on Engineering Structures

Due to the highly corrosive nature of sulfuric acid, some engineering structures are susceptible to corrosive attack. Materials such as steel and aluminium are particularly vulnerable to attack. Concrete structures used in bridges, culverts and pipes have also been degraded by acid derived from ASS (Lea, 1968, 1997).

The cost involved in replacing structures damaged or destroyed by acid attack is substantial. As a consequence of acid corrosion, many kilometres of cast iron water pipes in the NSW Tweed shire were replaced at a cost close to $AUD 4 million (White and Melville, 1996). Also, corrosion places the water supply at risk of contamination. Pipes are now made from PVC, or are specially coated to withstand corrosion. The construction of foundations, bridges and culverts on acid sulfate soils landscapes is also a major problem that can result in the inherent loss of soil structure causing buildings and other engineering works to become unstable due to earth movement (Dent, 1986). A common engineering practice often undertaken on soft sulfidic soils prior to engineering work, is the technique of consolidation, which requires the de-watering of these soils. This process involves pre-loading the soil surface (Smiles and Poulos, 1969) and using vertical wick drains to promote the de-watering of the loaded soil (White *et al.*, 2001b). The rate of de-watering depends on the hydraulic properties of the soil and the weight of the applied load. It may, however, be accelerated by soil acidification.

2.2.6 Health Impacts

To date, there has been very little evidence to suggest that there is link between the incidence of disease and the development or use of land containing acid sulfate soils. It has been suggested that changes to ecosystems can ultimately lead to changes in the biodiversity of an ecosystem and may therefore result in the possible emergence of new diseases (see Garrett, 1994; Dent, 1986). Some species of disease-carrying mosquito appear to seek out acid drainage waters for breeding, probably due to the absence of fish that normally feed on mosquito larvae (Easton, 2002). Disease carrying organisms, that are tolerant to acidified waters, may become well established in these environments (Green, 1993). This has serious implications, for the emergence of mosquito-born diseases and waterborne parasites, and is now a major threat to areas that up until now have been free of these diseases.

Perhaps one of the most serious health effects associated with the development of acid sulfate soils is exposure to sulfur dioxide gas. There is a possibility that residents living in regions affected by acid sulfate soils may be exposed to high levels of sulfur dioxide occurring as a result of pyritic oxidation. While nothing is known about the health effects of SO_2 from ASS, the effects of SO_2 from human activities, such as the burning of fossil fuels, are well documented.

Sulfur dioxide cannot be detected by the human olfactory senses at low concentrations. It readily reacts with water to produce sulfurous acid, often referred to as acid rain in fossil-fuel burning areas. This colourless gas usually affects people by constricting their lung passages often within a few minutes of exposure. Prolonged exposure to SO_2 may result in the development of respiratory and cardiovascular diseases, especially in people with pre-existing respiratory problems (Peters *et al.*,1996). The severity of sulfur dioxide exposure also increases with a rise in the level of SO_2 or from increased physical activity. The effects of SO_2 on human respiratory health can often be due to a synergistic effect where, for example, SO_2 exposure can be exacerbated by the presence of particulate matter in the air (Folinsbee 1992; Elsom, 1996).

Most of the morbidity studies that have been conducted on the impacts of SO_2, particularly in European cities, examined the relationship between the level of air pollution and the extent of hospital admissions by people suffering from respiratory problems. Results vary significantly from one city to the next and there has been much debate over what levels of exposure are acceptable for the various air pollutants.

Morbidity studies on air pollution have also been conducted in Australia. These examined the effects of air pollution on respiratory diseases, including asthma (Christie *et al* 1992; Rennick and Jarman, 1992; Derek, 1996). Morbidity rates in relation to SO_2 levels differ between studies depending on the region and the source of SO_2. Voigt *et al.,* (1998) found that there was no significant relationship between sulfur dioxide and respiratory morbidity for residents living in the Latrobe Valley, a highly industrialised centre in Southern Victoria. The maximum SO_2 level obtained in this area was 52 parts per billion (ppb), well below 170 ppb, the level acceptable in Victoria (Voigt *et al.*, 1998). The low levels of SO_2 recorded were due to the low sulfur content of the coal which is burnt by the majority of the power stations in the Latrobe Valley.

Perhaps one of the more important health concerns relating to ASS is the production of aluminium rich waters and the release of heavy metals into recreational and groundwater supplies. The effects of heavy metal poisoning on humans and its presence in the food chain are of major consequence to public health (See Pearce, 1995). There have been isolated cases where water supplies, contaminated with aluminium and heavy metals, have been used for domestic purposes in Australia and overseas (White and Melville, 1996). Aluminium is abundant in natural systems, however it is not required for biological processes by living organisms. Research has suggested that mental impairment and Alzheimer's disease are linked to the frequent ingestion of water rich in aluminium (Jacqmin-Gadda *et al.,* 1996). The effects of these contaminants on human health and their long-term social implications require further research.

2.2.7 Management of Acid Sulfate Soils

There have been numerous studies that examine ways to treat and/or prevent acidification of aquatic habitats from ASS (Singh *et al.,* 1988; Palko and Weppling, 1995; White *et al.*, 1997) including the correct management of Potential Acid Sulfate Soils (White and Melville, 1993). These range from the development of better watertable management practices to neutralisation using lime dosing. Unfortunately, the cost of treatment can sometimes outweigh the benefits. White *et al.,* (1997) demonstrated that the cost of using lime to completely treat a 4000 ha floodplain was estimated at around $AUD 250 million. Palko and Weppling, (1995) found that they were unable to sufficiently reduce the impact of acid runoff from agricultural land in Finland by using large quantities of lime.

However, despite the costs and difficulties of using lime to control pH, there are some indirect benefits associated with liming. The use of lime to control the effects of Al^{3+} toxicity has been successfully trialed on acid sulfate soils in Indonesia (Kselik *et al.*, 1993). This has also been beneficial in reducing the toxic effects of dissolved iron on certain plant varieties (Moore *et al.*, 1990).

Cheaper methods, apart from the use of lime, have also been trialed. Some farmers in Southern Kalimantan, Indonesia, use peat during cultivation to control pyrite oxidation. This method regulates the loss of water during the dry season and maintains a reduced state within the soil (Muhrizal Sarwani *et al.*, 1993). However, peat may not necessarily be an acceptable form of treatment for all crops or forms of cultivation and may have environmental impacts associated with its use.

2.2.8 Previous Work on the Modelling of Acid Sulfate Soils

To date, process modelling of ASS has been confined to the changes which take place within the soil environment (Bronswijk and Groenenberg 1993; van Wijk *et al.* 1993, van Breemen, 1993). There has been very little broadscale research carried out to examine the environmental factors such as climate and anthropogenic effects responsible for controlling the surface and groundwater dynamics in acid sulfate soil landscapes. Most of the research conducted in this area has focused on the physical and chemical aspects of pyrite oxidation within the soil profile.

Dent and Raiswell (1982) examined the effects of oxygen permeability on pyrite oxidation. They developed a model, which was able to predict the environmental effects of watertable lowering for the Gambian River. Bronswijk and Groenenberg (1993) developed a Simulation Model for ASS (SMASS) to predict the physical and chemical processes occurring in ASS in response to water management strategies such as drainage and irrigation methods. The SMASS model consists of a series of sub-models, which calculate water and solute transport and pyrite oxidation in response to oxygen diffusion and transportation through the soil. More recent studies have also modelled the behaviour of solute transport in acid sulfate soils (Rassam and Cook,

2001) including the ability to model the rate of acid generation in response to watertable height (Cook *et al.*, 2002b).

Although models such as SMASS attempt to explain the processes that take place in acid sulfate soils, they do not provide any insight into the broader impacts of these soils at the farm and catchment scale. They also tend to ignore the surrounding catchment hydrology and the spatial variability in climate, particularly rainfall and its impact on watertable dynamics and solute transport.

2.2.9 Hydrology of Coastal Acid Sulfate Lowlands

In ASS regions where severe acidification has made it almost impossible to treat by liming, because of the high costs, other appropriate water management strategies have been implemented (Tuong, 1993). Generally, water management strategies rely on the manipulation of the local hydrologic regimes of sulfidic lowlands to control or modify acidification. However, despite the practicality of using local water management strategies to control or prevent acidification, very little is understood about the hydrology of these sulfidic lowlands or the hydrological characteristics at the catchment scale. The coastal zones in eastern Australia experience a range of conditions from water logging to severe drought (White *et al.*, 1997). Streamflow and rainfall can also be highly variable depending on climatic weather patterns such as those influenced by El Niño and La Niña events. A fall in the watertable level below the sulfidic layer, either as a result of natural processes such as evapotranspiration (White *et al.,* 1993; Wilson *et al.,* 1999), or by human-made activities such as the construction of drains or floodgates, can lead to the oxidation of iron sulfides and the subsequent acidification of the soil profile.

The construction of drains and floodgates to control flooding and watertable levels has occurred on most of the sulfidic floodplains in southern eastern Australia. (White *et al.*, 1997). This practice has been encouraged by governments and local authorities and has resulted in dramatic changes to the hydrology of these floodplains. Floodgates can lead to considerable environmental problems often disrupting the natural flow of brackish water into floodplain tributaries. Recent studies have shown that brackish estuarine water fulfils an important function by neutralising small quantities of acid derived from small outflows (Sammut *et al.*, 1996). In effect, floodgates create acid reservoirs that allow continued leakage of acidified waters into river catchments and other estuarine environments. It has been proposed that the frequency at which these small acidification events occur could be minimised by the lifting of floodgates during dry periods to allow for tidal exchange (Sammut *et al.*, 1996). Farmers have cautioned against such moves, fearing that this would cause tidal waters to inundate the surrounding land and create possible salination problems (White *et al.,* 1999a). Apart from the problems associated with acidification, floodgates have also had a serious impact on fish populations by limiting their ability to migrate to natural feeding and breeding areas within backswamps (Sammut *et al.,*1996).

It is evident from the limited number of studies carried out on the hydrology of sulfidic floodplains (White *et al.,* 1993; Hamming and van den Eelaart, 1993; Tuong, 1993; Pease, 1995; Wilson, 1995; Wilson *et al.,*1999), that in order to manage these environments effectively, it is important to have an understanding of the broad catchment hydrology. Equally important, is the effect of climate and land management changes on the water balance of the floodplain over a given period of time and the control that this has on the transportation of acid reaction products through the catchment.

2.3 Institutional and Policy Issues

Numerous guidelines and policies have been developed by various government agencies in response to the environmental problems created by acid sulfate soils. Any land management or remediation strategy must be carried out in accordance with state and commonwealth policies. There are several key Commonwealth and State government policies that relate to the management and rehabilitation of acid sulfate soils and these have been outlined in more detail in a review by Tulau (1999b). Within the Commonwealth framework, there are four main policies that are particularly relevant to acid sulfate soils. These include:

(a) National Strategy for the management of acid sulfate soils. Australia appears to be the only country with a National Strategy on Acid Sulfate Soils. The Strategy emphasises the need for substantial investment in rehabilitation activities, including the introduction of incentives to encourage private and community investment in rehabilitation of coastal regions affected by ASS. The Strategy also acknowledges the need for greater awareness and communication strategies relating to acid sulfate soils. To facilitate the dissemination of information on ASS to researchers and the broader community, the Strategy recommends the development of Internet web sites containing content relating to a broad range of activities and information on all aspects of ASS.

(b) National Water Quality Management Strategy. This strategy is aimed at achieving better water quality through more sustainable use of water and greater protection of water resources. As part of the National Water Quality Management Strategy, water quality guidelines have been prepared for a number of industry and manufacturing groups.

(c) National Framework for the Management of Contaminated Sites. The Australian and New Zealand Environment and Conservation Council (ANZECC) and National Health and Medical Research Council (NHMRC) have defined a contaminated site as "an area containing hazardous substances in excess of the recommended levels and which pose either an immediate risk or a long-term risk to human health" (ANZECC/NHMRC, 1992). This policy is particularly relevant to acid sulfate soils because of their associated health risk from acid by-products such as aluminium, heavy metals and sulfur dioxide. There is a potential for long-term health problems in regions where there is high residential development on ASS landscapes. In some states such as Victoria, ASS regions have been classified as contaminated sites (Atkinson, personal communication, 2000).

Apart from Commonwealth policies, there are several State and Local government initiatives concerned with the environmental management and control of acid sulfate soils. With continued conflict between the farming and aquaculture industry groups, the State Government of NSW established the Acid Sulfate Soils Management Advisory Committee (ASSMAC) in 1994, to provide advice to the government on a range of matters relating to the management of acid sulfate soils. Since there are many policy and institutional matters that affect a range of different government departments and industry sectors, ASSMAC has attempted to provide a whole-of-government approach in providing solutions to the problem. Since its inception, ASSMAC's role as an advisory body has gradually been widened to include industry and other stakeholders affected by acid sulfate soils (White, 2001a). The industry groups that are most affected by acid sulfate soils either directly or indirectly include:

- Sugar
- Oyster
- Fisheries and Aquaculture
- Dairy
- Tea Tree
- Tourism
- Development

Some industry groups, such as the oyster and sugar cane industry are particularly active in relation to the proper management of these soils. The oyster industry, for example, has sustained substantial losses in production, not just from the effects of acidification but also from sewage and stormwater discharge into estuarine systems (White, 2001a). Other industry groups, such as the Tourism and Tea Tree industry are not as well versed on the impacts their industry is having on the environment (Woodhead, 1999). A distinct lack of awareness and education relating to best management practices for ASS appear to be a major problem recently identified by some industry groups (Woodhead, 1999).

Both local and state government plans have been particularly important in protecting regions that contain potential acid sulfate soils. The NSW State Environment Protection Plans (SEPP) such as the coastal wetlands SEPP 14 are very effective at preventing development in regions that are particularly prone to environmental degradation through acidification. Local Environment Plans (LEPs) have also been successfully applied to acid sulfate soils in NSW. The Department of Planning NSW (previously NSW Department of Urban Affairs and Planning, DUAP) and ASSMAC have encouraged local councils to adopt LEPs as a regulatory strategy for controlling development on land containing ASS. The Hastings Council followed by the Tweed Shire Council were the first local authorities to apply this strategy to ASS.

The institutions and organisations involved in the management and rehabilitation of acid sulfate soils in Australia is shown in Figure 2.1.

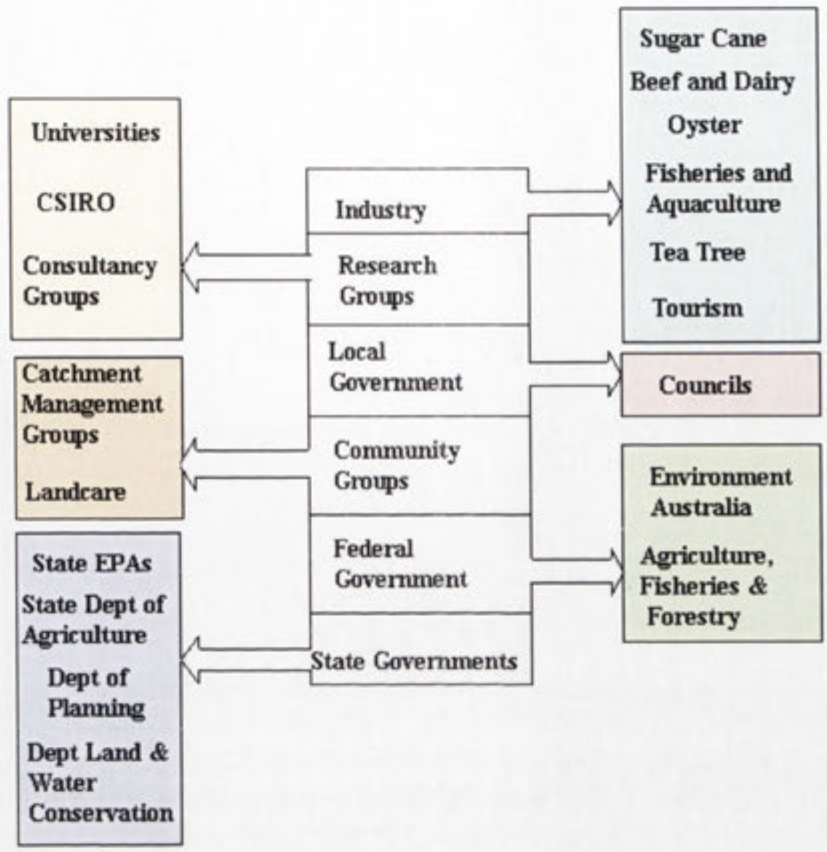


Figure 2.1 Breakdown of institutions and organisations involved in the management of acid sulfate soils in Australia.

CHAPTER 3
Integrated GIS-Hydrological Models

Chapter 3. Integrated GIS-Hydrological Models

3.1 Introduction

An understanding of the climatic conditions within coastal acid sulfate soil catchments is a fundamental factor in predicting the pattern and magnitude of acid discharges into receiving environments. At present there is no general, broad use, systematic way of determining the impact of land changes in land and water management strategies on the export of acidity in coastal floodplains. To date, most strategies rely on site specific, localised action to determine the impact of land use on water quality, rather than on examining broader influences, such as the surrounding catchment hydrology or the inherent spatial and temporal variability of climate. An understanding of the impact of land management changes on water quality at the catchment scale is more useful for managing estuarine systems. Here we shall concentrate on coastal catchments in NSW. Figure 3.1 shows the coastal catchment areas of NSW.

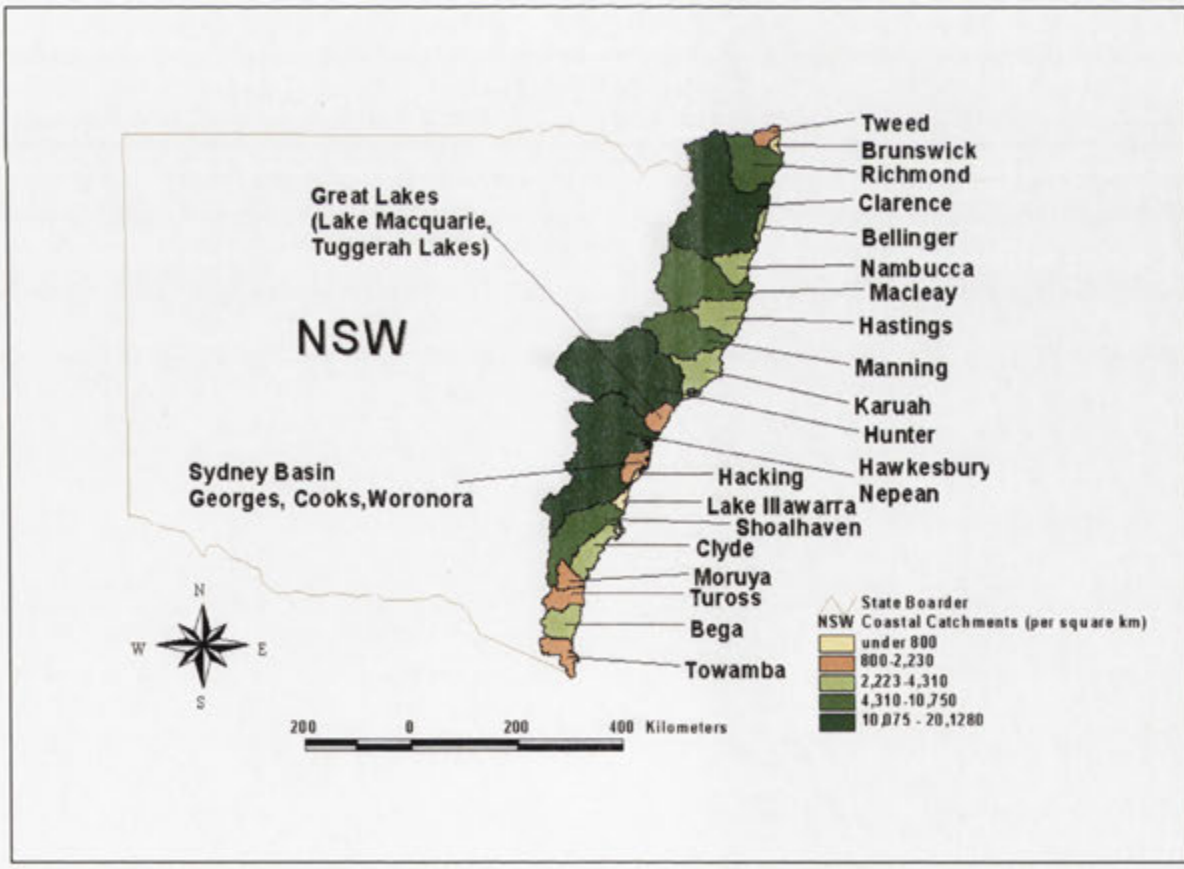


Figure 3.1 NSW Coastal Catchments by Area.

NSW coastal river catchments vary significantly with respect to runoff. The NSW Resource and Conservation Assessment Council (RACAC, 1995) has made estimates of the annual percentage runoff for several major coastal catchments in NSW and these are shown in Figure 3.2. Smaller catchments such as the Tweed and Brunswick have a higher percentage of runoff than larger catchments like the Clarence and Macleay. It is logical to suggest that smaller catchments with a greater runoff potential would have a greater impact on water quality. The average annual percentage runoff for NSW coastal catchments is approximately 27% (White *et al.*, 1999a) compared with the average annual percentage runoff for all of Australia of only 8% (Smith, 1998). In terms of acid sulfate soils, regions that have a high ratio of ASS to area of catchment such as the Tweed, Cudgen and Brunswick, are regarded as having high potential environmental risk from ASS. Figure 3.3 shows the area ratio of ASS for the major coastal catchments of NSW.

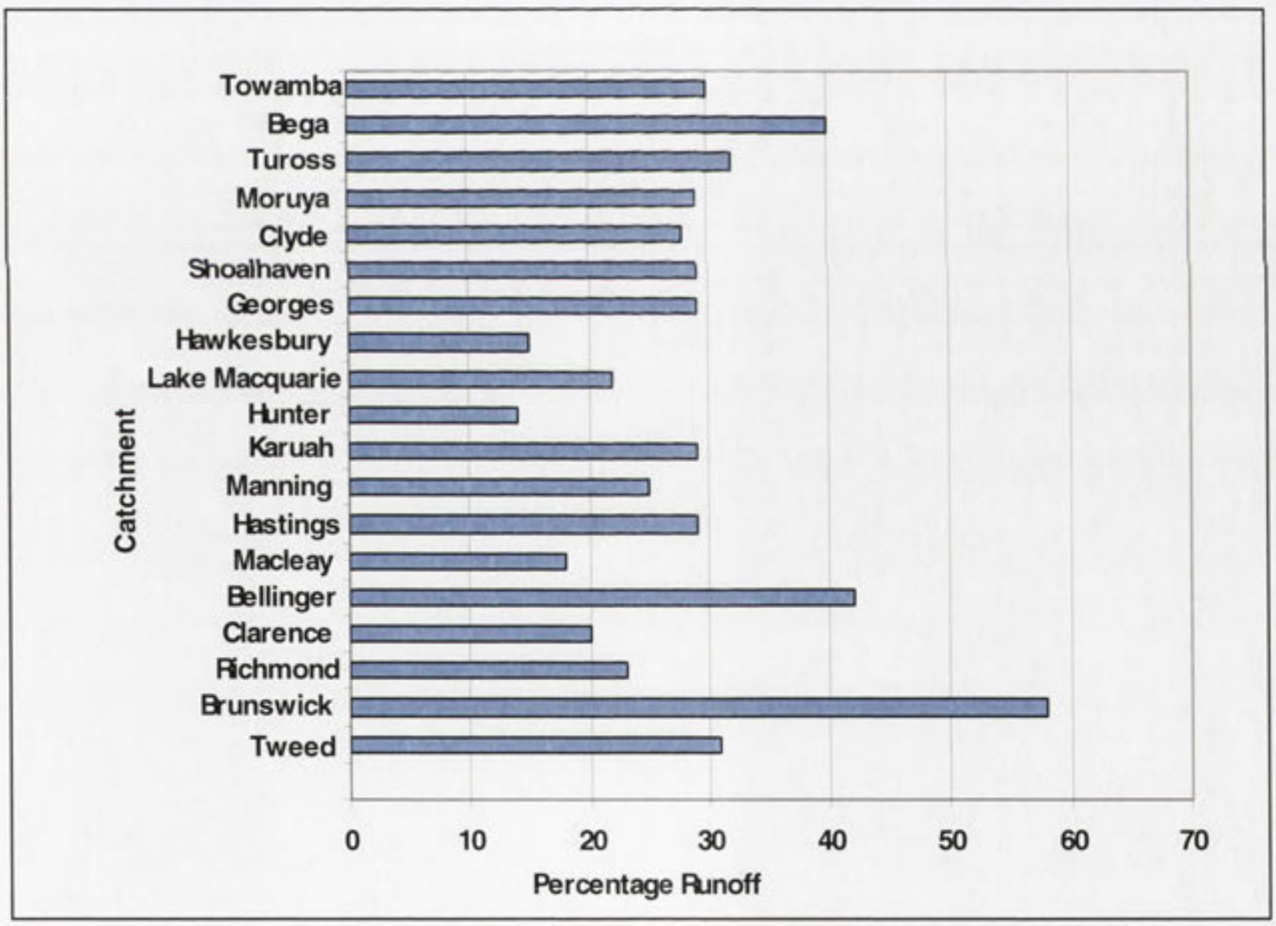


Figure 3.2 The percentage runoff for a number of NSW coastal catchments with acid sulfate soils. Blue line indicates the mean for NSW (RACAC, 1995).

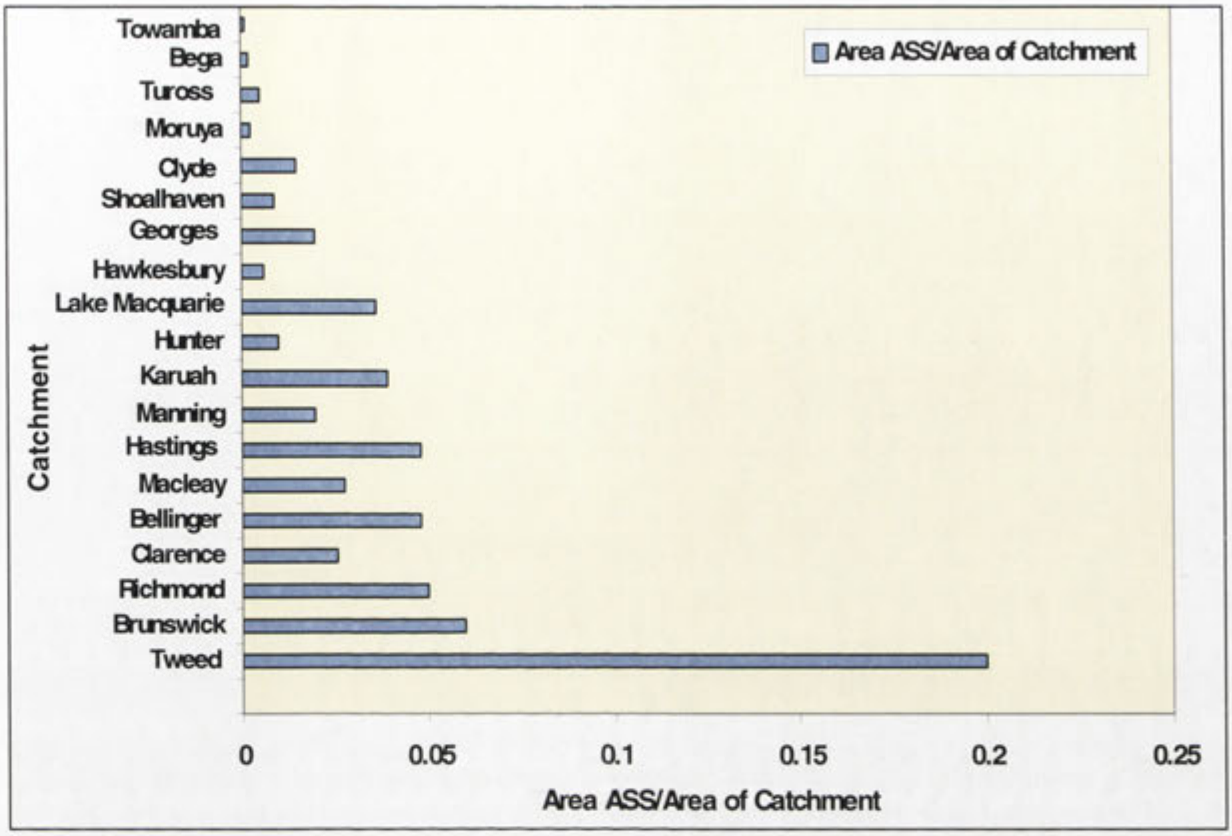


Figure 3.3 Area of high risk ASS/area of catchment for NSW coastal catchments (White et al., 1999a).

Since every catchment has its own set of attributes, it is very difficult to generalise about water quality impacts between coastal catchments. The main objective of any water quality model is to be able to predict when water quality problems are most likely to impact on the catchment, including the ultimate fate of the pollutant. It is obvious that the range of hydrological and water resource issues faced by catchment managers are of a spatial as well as temporal dimension. This chapter examines the issues surrounding hydrological water quality modelling and the methods available for assessing the downstream impacts from climate processes and land management decisions.

3.2 Estimating Pollutant Sources from Rainfall-Runoff Modelling

There are four basic hydrological model types used in hydrology: lumped parameter, spatially distributed, physics-based and hybrid models. The advantages and disadvantages of each type and their application to hydrological modelling, are outlined in a review by De Vantier and Feldman (1993). Out of the four basic model types, the lumped parameter model an example of which is the Hydrologic Engineering Center's (HEC) Flood Model HEC-1, is most widely used to model rainfall-runoff process and to assess the impact of pollutants on aquatic ecosystems (Warwick and Haness, 1994). Lumped parameter models employ a number of lumped parameters such as drainage area, terrain and elevation, to model hydrological responses. The properties of these spatial features are averaged over the catchment (Maidment, 1993). However, the distinction between lumped and spatially distributed models is not always clearly defined (Olivera and Maidment, 1997; Olivera *et al.*, 1997).

The terms point and non-point pollutants are often used to describe sources of pollutants. Hydrological water quality models have been developed for a range of non-point and point pollutant sources. Point-source pollutants are far more easily identifiable than non-point pollutant sources due to the fact that they generally originate from specifically identifiable locations such as sewage and industrial treatment plants. A non–point pollution source is defined as a pollutant that is transported from dispersed land sources to streams and river systems (Lane, 1983). They are more difficult to identify due to the spatially distributed nature of the processes associated with the type of pollutant source. It can be argued that acid and heavy metal discharges originating from acid sulfate landscapes can either represent a point or non-point pollutant source depending on whether man-made structures, such as drains and floodgates, play a part in regulating discharge. For the purpose of this thesis acid sulfate soils will be treated as a non-point pollutant source.

Non-point pollutant sources are suited to modelling using temporal properties, such as rainfall, and spatial features such as land use. The use of detailed site specific experiments to determine the extent of the non-point pollution problem is simply not feasible due to the time and cost involved in collecting and interpreting the data (Engel *et al.*, 1993). For this reason, simple lumped parameter or spatially distributed models based on rainfall-runoff processes are more commonly used to measure nutrient or pollutant transport (Olivera and Maidment, 1997) or to assess the impact of runoff on erosion and sediment transport (De Roo, 1998).

3.2.1 Water Balance Issues for Coastal Floodplains

An understanding of the catchment's climate and landscape characteristics, such as rainfall, evaporation and evapotranspiration, is needed to determine the water balance of the floodplain. Evapotranspiration describes both transpiration by plants and direct evaporation from water bodies and the soil (Brutsaert, 1982). Previous studies (Walker, 1972; Tuong, 1993; White *et al.,* 1993; Wilson, 1995) have shown that the management of acid outflows from coastal catchments containing acid sulfate soils is dependent on a detailed knowledge of three main factors. These are:

(a) the distribution of sulfuric acid and sulfidic soil layers below the soil surface,
(b) the watertable dynamics and how it interacts with the sulfuric and sulfidic layers and
(c) the effects of climate and land management activities on the watertable dynamics and export of sulfuric acid.

3.2.1.1 Streamflow

The export of acidic groundwater to surface waters is influenced by two important characteristics of rainfall, namely the ratio of runoff to precipitation and its variability with respect to time. For coastal catchments with acid sulfate soils the quality and quantity of water is influenced by the water balance of the catchment (White *et al.*,1997). The water balance for a catchment over any time period can be written as:

$$P + I = RO + R + ET \pm \Delta S \qquad 3.1$$

Inputs Outputs Storage

where P is the precipitation, I is any irrigation, RO is runoff including surface and subsurface lateral outflow, R is groundwater recharge, ET is evapotranspiration and ΔS is the change in the soil and surface water storage. The soil water storage above the watertable is usually measured in depth per unit of surface area (mm). The change in soil water storage over long periods in coastal floodplains is generally negligible compared to rainfall and precipitation. Irrigation (I) in equation 3.1 is generally not considered because in Australian coastal floodplains there are limited opportunities for irrigation, except where tea tree plantations are grown during the drier months (White *et al.*,1997). Clearly, the two main components of the water balance are precipitation and evapotranspiration. Rainfall, pan evaporation and streamflow, follow very similar trends through the year suggesting that these are key factors in the hydrological cycle (See White *et al.,*1997).

Equation 3.1 can therefore be simplified as:

$$P = RO + ET \qquad 3.2$$

The changes in precipitation and evaportranspiration with respect to time, determines the long-term outflow from the catchment. The runoff, *RO* for any time period is defined as:

$$RO = CxP \quad (mm / yr) \qquad 3.3$$

Here *C* is the runoff coefficient and *P* is the catchment areal mean precipitation (mm). An important parameter is the ratio of runoff to rainfall. The runoff coefficient is therefore:

$$C = \frac{RO}{P} \qquad 3.4$$

The spatially averaged precipitation for the catchment is:

$$P = \int P' dA / A \qquad 3.5$$

Where *A* is the drainage area and *P*` is the spatially distributed mean annual or monthly precipitation. Finally, the surface runoff is related to the stream discharge *Q* through:

$$RO = \frac{Q}{A} \qquad 3.6$$

In northern and eastern Australia, there is a strong correlation between El Niño and La Niña events with extreme variability in monthly rainfall and streamflow from year to year as illustrated in Figure 3.4. El Niño events are generally associated with warmer ocean temperatures and drier conditions (Power *et al.,* 1999a).

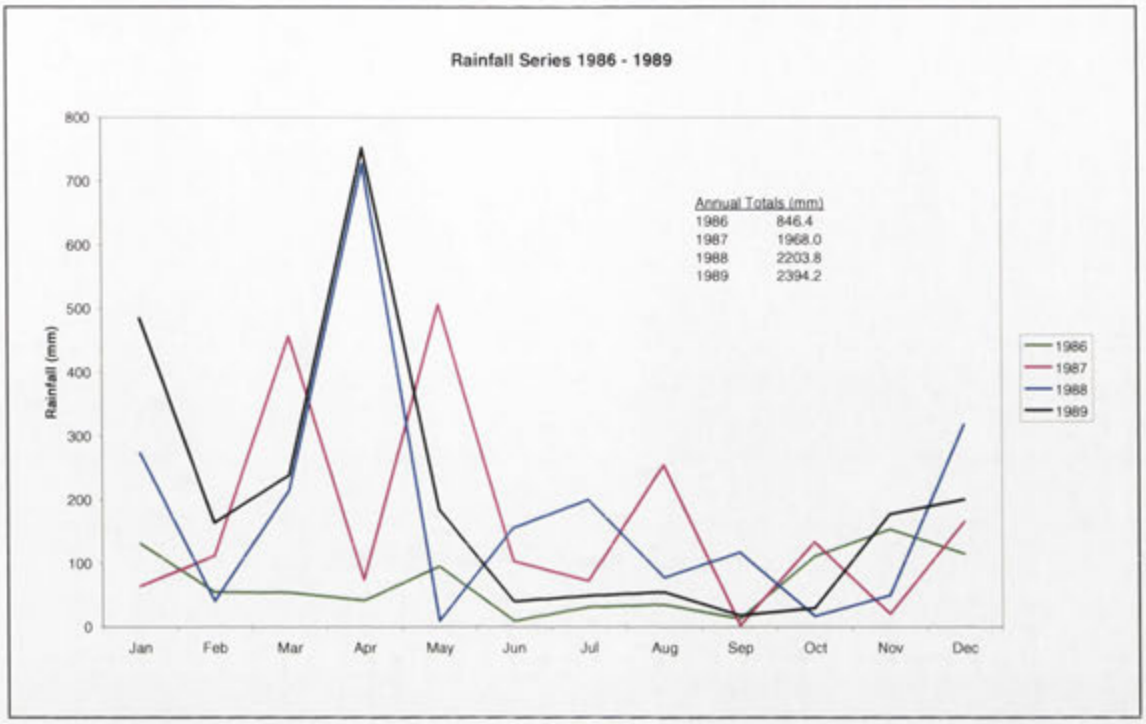


Figure 3.4 Variability in monthly rainfall for the Tweed between 1986-1989 (M. Tunks, Tweed Shire Council).

3.2.1.2 Shallow Groundwater

The change in the shallow watertable height, ΔH, for any time period, is dependent upon the vertical drainage, (D), L_{gi} (Lateral groundwater inflows) and L_{go} (Lateral groundwater outflows), watertable evaporation, E_g, and specific yield (porosity) of the soil, Y_g .

$$Y_g . \Delta H = D + L_{gi} - E_g - L_{go} \qquad 3.7$$

Storage Inputs Outputs

Comparing equations 3.1 and 3.7, the groundwater evaporation (E_g) is less than or equal to the evapotranspiration, ET and the groundwater recharge rate (R) is therefore defined as:

$$R = D - E_g \qquad 3.8$$

Unlike unoxidised estuarine clay sediments which have low permeability to water, oxidised sediments have a greater permeability to water and therefore, in many ASS floodplains, rainfall quickly infiltrates the soil resulting in very little direct surface runoff (White *et al.*, 1993; Wilson , 1995; White *et al.,* 1997; Wilson *et al.*, 1999). The unoxidised sulfidic sediments can act as an impermeable barrier to rain water resulting in higher surface water runoff into streams and drains.

During periods of heavy rainfall significant surface runoff will occur in coastal floodplains when the shallow watertable reaches the soil surface. This is also the period when stored acid is mobilised in the soil profile from raising watertables and transported to the surface where it becomes runoff to agricultural drains and streams. When the watertable falls during dry periods due to evaporation (ie, when D, L_{gi} and L_{go} in equation 3.7 are equal to zero) the sulfidic layer may become exposed to air, resulting in further oxidation of PASS.

The change in the soil water storage (equation 3.1) in unconsolidated ASS is, typically, not greater than 50 mm. During wet periods this change is negligible. The lateral inflow during wet periods from the upland areas is dependent upon the upland catchment area (A_c), the rainfall in the upper catchment (P_c) and the proportion of rainfall (r_c) that results in inflow to the floodplain area (A_f). The lateral inflow is expressed as:

$$L_i = \frac{P_c r_c A_c}{A_f} \qquad 3.9$$

In very wet periods $P_c \approx P`$, $r_c = 1$ and ponded surface water, ΔS_p , becomes the only store. Thus, the water balance for the floodplain becomes:

$$P`\frac{A_f + A_u}{A_f} \approx E_T + L_o + \Delta S_p \qquad 3.10$$

In eastern Australia $\frac{A_u}{A_f}$ is normally of order 10 so that the up catchment inflows dominate the floodplain water balance in very wet periods. During dry periods, the inflows, drainage and outflow are zero and equation 3.7 becomes:

$$Y_g . \Delta H = -E_g \qquad 3.11$$

Under these circumstances the watertable dynamics is solely influenced by watertable evaporation. This is in turn influenced by type of vegetation (leaf area and rooting depth), solar radiation, humidity, radiation, wind speed, air temperature and pressure, hydraulic properties of the soil, soil water availability, as well as the position of the watertable (White *et al.,* 1997). Groundwater evaporation is usually related to potential evaporation (E_p) which refers to the rate of evapotranspiration from well-watered vegetation (Brutsaert, 1982).

There are many methods that have been used to determine the actual evaporation (E_t) from potential evaporation that take into account the impacts of plants and soils. The equation:

$$E_t = C_t x \quad E_p \qquad 3.12$$

uses a time-dependent crop factor (C_t) to calculate actual evaporation (E_t). For bare soils the (C_t) factor can be close to 0.5 while for a well-watered crop (C_t) is close to 1. Pan evaporation rates are often used in situations when potential evaporation (E_{pan}) rates are unavailable and can be estimated from the pan coefficient (P_{co}) (Penman, 1948). Pan coefficient data is available for a number of lakes around Australia (Hoy, 1977 and Hoy and Stephens, 1977). The potential evaporation for a particular year when the season is wet is given as:

$$E_p = P_{co} x \quad E_{Pan} \qquad 3.13$$

When there is a good soil water supply and adequate vegetation cover, it has been shown that there is a strong correlation between evapotranspiration from vegetation and pan evaporation (Pruitt, 1966; Mullroy and Angus, 1964).

3.3 The Application of GIS to Hydrological Modelling

An essential characteristic of a GIS is its ability to provide spatial information about the surface of the land. Both GIS and hydrological modelling are inextricably linked to each other. Perhaps one of the greatest benefits in linking GIS with hydrologic models, is the ability of a GIS to represent the surface of the land in a digital database on which a hydrological model can be developed (Maidment, 1993). Fundamentally, the GIS also provides a user interface for viewing these models in a spatially distributed way. Since hydrologic processes are driven by time-dependent factors such as rainfall, it is possible to create a steady-state model consisting of time-dependent data forms by averaging a series of events over specified time periods (Maidment, 1993).

The use of GIS for rainfall-runoff modelling has taken many different forms ranging from the use of vectors (Silfer *et al.*, 1987; Vieux *et al.*, 1988) through to a raster-based GIS (Wolfe and Neale, 1988). The investigation of any hydrological process or water quality issues, requires the development of a catchment model that employs physiographic information such as land surface elevation, as well as the distribution of stream networks within a given catchment. This information is derived from a digital representation of the landscape topography known as a Digital Elevation Model (DEM). Most DEMs can be presented as regular grids or as Triangular Irregular Networks (TINs). The grid data structure is the most common due to its high degree of computational efficiency (Martz and Garbrecht, 1992). A regular grid does have disadvantages including the inability to accommodate certain complex topographical surface features without the need to alter the grid size (Burrough and McDonnell, 1998).

The Triangular Irregular Network (TIN) (Peuker *et al.,* 1978) allows additional information on topographical features, such as slope, to be made available in regions of complex relief without the need for additional data. A TIN employs a continuous network of triangles containing nodes from which slope and aspect are defined. The modelling used in this thesis was developed from methods described by Jenson and Domingue (1988) in which the DEM is based on grid cells of uniform size. A TIN approached was used in Chapter 8 to display the finer topographical features of cane blocks.

The use of DEMs for hydrological modelling has allowed for the identification of drainage features such as floodplains, ridges, mountains, stream and river networks, as well as natural and man-made surface drainage characteristics (Martz and Garbrecht, 1995). The accuracy of these topographical characteristics is dependent on the quality of the raw topographical data and the quality and resolution of the DEM together with the algorithms that provide a degree of functionality necessary for performing certain functions, such as catchment delineation (Martz and Garbrecht, 1992). An interpolation algorithm has been developed by Hutchinson (1989) that uses elevation data points and streamlines to produce a DEM that accurately represents the features of the landscape. Studies have shown that DEMs developed using this algorithm are more accurate than DEMs derived using other interpolation methods (Olivera *et al.*, 1997; Xang, 1997).

The issue of spatial scale or resolution is also an important factor associated with DEMs. Different climate variables and earth surface processes have varying scales of topographic dependence (Hutchinson, 1991). These climate variables include those associated with hydrological processes such as evaporation, rainfall and runoff. The fine-scale DEMs are those with spatial resolutions ranging from 5 to 50 metres, generally used for spatially dependent hydrological modelling (Binley and Beven, 1992).

The “fine mesoscale” or “toposcale“ DEMs generally have spatial resolutions ranging from 50 to 200 metres. Spatial resolutions of this scale are suitable for modelling miroclimatic changes (Hutchinson, 1998) and its impacts on vegetation distribution and growth (Wigmosta *et al.,*1994). This scale can also be used for sub-catchment delineation where lumped parameter hydrological models are used and for broad-scale hydrological modelling (Maidment, 1993).

DEMs with spatial resolutions ranging from 200 metres to 5 kilometres are classed as “mesoscale” and are suitable for modelling climate variables, such as rainfall and surface temperature (Hutchinson, 1998). Elevation rather than topographical detail is much more crucial when modelling these types of variables (Hutchinson, 1998). Spatial resolutions ranging from 50 to 500 kilometres are classed as "macro scale" and are suitable for broad-scale atmospheric modelling. The determination of a satisfactory spatial resolution for use in hydrological modelling is a contentious issue (Bloschl and Sivaplan, 1995).

There are many hydrological software programs that use DEMs for modelling the impact of time and climatic influences on the hydrological processes which take place within a catchment. Many of these programs have been incorporated into a Geographic Information System (GIS) which allows for a systematic approach to analysing and managing water resources (Moore *et al.,* 1991; De Vantier and Feldman, 1993). Therefore, the first objective in linking GIS with hydrological modelling is to devise a suitable GIS that can be used not only as an information tool but will also allow hydrological and other modelling tools to be incorporated into the GIS in order to predict water quality in response to land changes and climate.

3.3.1 GIS Hydrological Based Models

Numerous GIS hydrological-based models have been developed for predicting the movement of surface pollutants from agricultural and non-agricultural landscapes. Saunders and Maidment (1995) used a GIS grid-based water quantity and quality model for determining pollutant loads in the San Antonio-Nueces coastal catchment of Texas. The model used observed runoff at flow gauging stations and a precipitation grid to develop a regression equation that predicts expected runoff as a function of precipitation.

The Agricultural Nonpoint Pollution Source Model (AGNPS) (Young *et al.,* 1989) developed by the US Department of Agriculture-Agriculture Research Service, is a grid-based model, used to predict erosion and water quality resulting from a single storm event. AGNPS has been integrated with the Geographic Resources Analysis Support System (GRASS) GIS, developed by the US Army (1987), as a decision support tool for managing erosion and nutrient transport within catchments (Engel *et al.,* 1993).

Another common non-point source pollutant model is the Areal Non-point Source Watershed Environmental Response Simulation (ANSWERS) developed at the Agricultural Engineering Department, Purdue University (Beasley and Huggins, 1982). The ANSWERS model calculates hydrological and erosion responses in agricultural catchments. ANSWERS has been linked to various GIS and imaging processing systems, including GRASS (Engel *et al.,* 1991), the Earth Resources Analysis Support System (ERDAS) and Arc/Info packages (Moore *et* al., 1993). ANSWERS requires catchment topography, soil, land use and drainage characteristics for analysis and can be used to analyse data either at the catchment scale or on an individual grid cell basis (Quenzer, 1998).

3.3.2 Limitations of GIS Hydrological Systems

The above discussion has provided a brief overview on the applications and benefits of GIS hydrological systems to environmental management. The limits imposed on effectively linking GIS and hydrological models are varied but according to Maidment (1993), critical limitations often become apparent when dealing with a multitude of different data models within a GIS environment. A GIS is very effective at processing large data sets on individual themes or layers over a wide area. However, from a hydrological modelling perspective, quite often the requirements expected from a GIS are usually local instead of global in nature, with many researchers concerned mainly with modelling small areas within catchments (Maidment, 1993). There are also GIS/hydrological linkage problems associated with large quantities of spatial data that exist in unorganised formats (Yoon, 1996).

One of the greatest limitations associated with GIS is the difficulty in modelling environmental phenomena that have strong time-dependent factors (Maidment, 1993). Unfortunately, hydrological analyses fall into this category in which time variation is an important element in understanding hydrological responses, such as the rate of nutrient transport through catchments or the variability in flow within estuaries in response to tidal exchange. For now, the role of a GIS-hydrological linked model is limited and can only provide a "snapshot" of a particular event in time or averaged over a period of time (Maidment, 1993).

Another limitation associated with hydrological systems linked to a GIS environment is the dependence on software compatibility, especially when transferring data from one software system to another. For example, data manipulations involving the transfer of data from a map/info environment to an arc/info environment (Piwowar and LeDrew, 1990). Many of these procedural problems have only recently been addressed, however, there are still incompatibility problems, especially those associated with displaying hydrological GIS models through various web site interface systems. Considerable programming and software development is still required in order to solve this problem. Some of these issues are discussed in Chapter 10 of this thesis.

CHAPTER 4
Development of a GIS-Hydrological Model for the Tweed Catchment

Chapter 4. Development of a GIS-Hydrological Model for the Tweed Catchment

4.1 Introduction

This chapter describes the development of a GIS hydrological model for the Tweed Catchment in far northern NSW. This catchment has a high area of ASS/area of catchment compared with other NSW coastal catchments containing ASS (See Figure 3.3, Chapter 3) and has been designated as an Acid Sulfate Soils management priority area by the Acid Sulfate Soils Management Advisory Committee (ASSMAC, 1999b). The Tweed Catchment is located on the far north coast of New South Wales (Figure 4.1) situated between latitudes 28 ^{0} 10 ^{I} S and 28 ^{0} 30 ^{I} S and longitudes 153 ^{0} 06 ^{I} E and 153 ^{0} 33^{I} E and having a total area of 1080 km^2. The catchment has a radial drainage pattern, with the Mount Warning Shield Volcano the dominant landscape feature. The Tweed River is fed by two main tributaries, the Rous and Oxley Rivers. Three sub-catchments were delineated and subjected to hydrological analysis. These are the Uki, Eungella and Cudgen sub-catchments. A digital representation (DEM) of the catchment is shown in Figure 4.4.

Figure 4.1 Tweed Catchment study area.

4.2 Methodology

4.2.1 Map Projection

A suitable projection was chosen that would permit new themes or surfaces to be added to the DEM with a high degree of accuracy as well as to allow for the correct spatial modelling of features such as flow rates and flow accumulation. The Universal Transverse Mercator System (UTM) was chosen as the most suitable and widely used projection for finer scale topographic mapping and hydrological analysis. This projection divides the world into 60 north-south zones with each zone spanning six degrees of longitude, about a central meridian. The UTM system also maintains angular relationships at a local scale, thus providing a high degree of flexibility in plotting exact locations with different data sources much more efficiently than with latitude and longitude measured in degrees, minutes and seconds (Terry, 1996). A majority of worldwide topographic metric maps with a scale range of 1:24,000 to 1:250,000 commonly use this type of projection.

4.2.2 Development of a Digital Elevation Model Using the ANUDEM Program

For hydrological modelling it is essential to be able to construct a DEM that provides an accurate representation of land features and drainage characteristics. Triangulation and non-adaptive direct gridding, are common methodologies used to interpolate DEMs from topographical maps. However, these methods have limitations when contour data (the most common topographic data) is used as a data source. These methods also fail to accurately represent slope and curvature of the land, essential criteria in hydrological modelling (M. Hutchinson, personal communication, 1999).

In this section the ANUDEM program, developed by Hutchinson (1989, 1996, 2002a), was used because of its ability to interpolate a grid-based DEM from standard digital topographic contour data. The program uses an algorithm that interpolates the elevation data by minimising a terrain-specific roughness penalty (Hutchinson, 1998) on the fitted DEM grid data, as well as imposing locally adaptive constraints that ensure proper representation of shape and drainage structure derived from input contour line data.

4.2.2.1 Local Adaptive Smoothing of Discretisation Error

An important feature of the ANUDEM program is locally adaptive smoothing of discretisation errors. Digital elevation data are generally assigned to the centre of the closest grid cell. This results in a small positional error that can be interpreted as a vertical error. This is illustrated in Figure 4.2 where data point A, which represents the true value on the sloping surface, is allocated to the centre of the grid cell C, resulting in a horizontal displacement d and a vertical error Z.

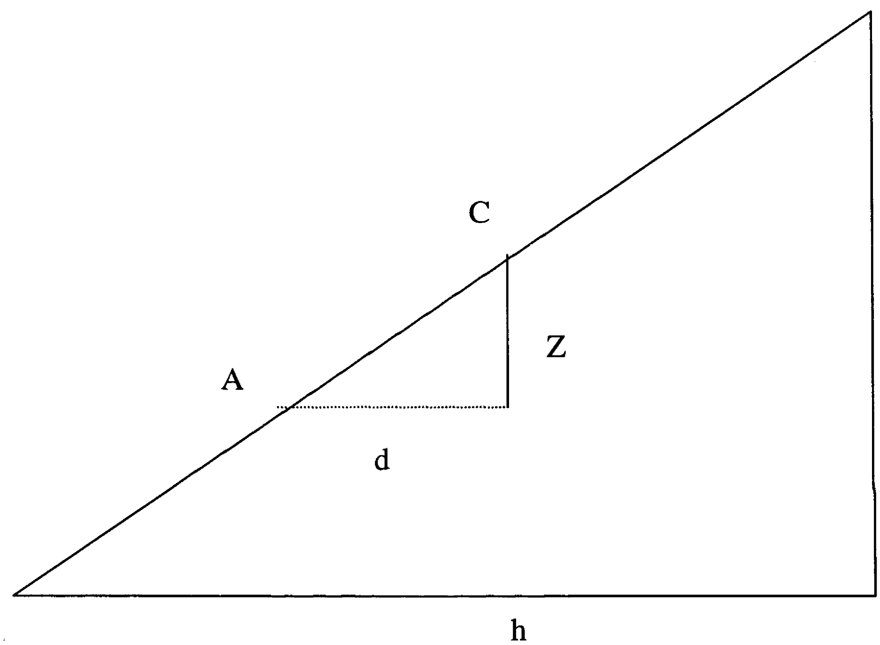


Figure 4.2 Vertical error resulting from displaced data point (Adapted from Hutchinson, 1996).

The magnitude of the vertical error (Z) is dependent on the slope (*S*) of the landscape across the grid cell and the horizontal displacement such that:

$$Z = d * S \tag{4.1}$$

Assuming the displacement is randomly placed within the grid cell, the variance *V* can be derived to be:

$$V = h^2 S \big/ 12 \tag{4.2}$$

Where h is the width of the mid point of the grid cell (Hutchinson, 1996). The standard deviation is expressed as:

$$SD = h\ S \Big/ \sqrt{12} \qquad 4.3$$

Elevation data points are weighted by ANUDEM according to their error variance given by equation 4.2. The degree of data smoothing is determined by setting the smoothing parameter so that the average of the squares of the weighed residuals is equal to 1.0. Therefore the extent of smoothing is locally adaptive to the slope of the terrain. However, because slope is a function of terrain, it is necessary to interpolate terrain surface before the slope can be specified. This is possible because ANUDEM is an iterative technique.

4.2.2.2 Drainage Enforcement Algorithm

To ensure the development of a satisfactory drainage structure, necessary for hydrological analysis, the ANUDEM program also imposes a drainage enforcement algorithm, which automatically identifies spurious sinks in the grid data (Hutchinson, 1989; Hutchinson and Dowling, 1991). Sinks and pits are uncommon in nature (Mark, 1984) and are usually removed from the data as they have a tendency to disrupt natural water flow paths during modelling. The ANUDEM drainage enforcement algorithm eliminates the need for manual correction of elevation grid data to remove spurious drainage characteristics. The characteristics of the ANUDEM program are shown in figure 4.3.

The occurrence of sinks in the DEM is often due to incorrect or insufficient data. For the development of the Tweed DEM, sinks were removed through the addition and /or removal of incorrect height data. The presence of incorrectly positioned contour or spot height data can result in the formation of sinks within the DEM. In the later work presented in this thesis, artificial sinks are included in some of the DEMs produced for the purposes of hydrological analysis. Sinks are added to the DEM grid data to determine the total pollutant constituents at certain points in the stream network and to model surface water volumes.

4.2.2.3 DEM Development and Data Source

A 100 metre spatial resolution DEM of the Tweed Catchment was created in ARC/INFO (UNIX Version 8.02) using the ANUDEM (Version 5). The input data used to create the DEM included streamlines derived from 1:125,000 spot height data derived from contours on 1:100,000 topographic map-sheets maps and trig stations (AUSLIG, 1992). The 1:100,000 topographic map sheets were used as a manual check for the correct elevation. A full drainage analysis was also performed as an additional test for drainage artifacts and the delineation of catchments by using the flow accumulation method described by Jenson and Domingue (1988).

Source data was projected to UTM and the DEM fitted to the projected source data. The DEM was created in ASCII Grid file format before it was converted to an ARC/INFO Grid Coverage and then imported as a theme to ARCVIEW version 3.2 (Environmental Systems Research Institute). Streamlines were incorporated into the DEM as a theme in ARCVIEW.

Figure 4.4 shows the computed 100 metre DEM of the Tweed Catchment including the sub-catchments of the Cudgen, Uki and Eungella. These smaller catchments were delineated using the flow accumulation method of Jenson and Domingue (1988). A shaded relief theme was also constructed (Figure 4.5) as a visual inspection for local anomalies that can usually appear as dark spots (Hutchinson, 1997). Shaded relief is a graphical procedure, which can also be used to check land features such as slope and aspect in the DEM. Some authors (Hunter and Goodchild, 1995) recommend this tool for detecting edge matching difficulties that can be encountered with some types of DEMs. A 3D analysis of digital surface data was also conducted using the visualisation software Vistapro (Version 4.01) (Hinkley, 1990) (Figure 4.6). Vistapro 3D analysis provides a far more realistic visual inspection of the DEM. The use of 3D analysis for viewing, requires specialised software not normally found in standard GIS software packages (Nichols *et al.,* 1992). Visualisation as a communication tool is discussed in more detail in chapter 10 of this thesis.

Another useful assessment of DEM quality, is the ability to derive contours from the DEM. Errors in digitising from topographical maps, do occur regularly, particularly if the contour maps are not clearly labelled. Contours derived from the DEM can accurately detect errors in the source data making this procedure a good check of possible elevation errors. Contours were derived from the DEM and compared with the mapped contour data as an additional check for errors. The ANUDEM parameters used in the development of the DEM are summarised in Table 4.1.

Table 4.1 ANUDEM User Directives for Tweed DEM.

PARAMETER	VALUE	COMMENTS
Drainage enforcement	1	0-No enforcement, 1- enforcement, 2-enforcement with voluminous sink diagnostics
Contour data option	0	0 – data consists mainly of spot heights 1- data mainly of contours
Discretisation error factor	1.0	The discretisation standard error factor should be set to 1.0 unless the data have significant random (non-systematic) horizontal errors.
Vertical standard error	0.0	For most elevation data sets the vertical error is zero.
Roughness penalty	0.5	0.5 (for a mixture of curvature and potential spot height data) 0.0 for minimum curvature (for contour data)
Elevation tolerance	8 m	This is dependent on the accuracy of the elevation data. Typical value for point data at a scale of 1:100,000 are 5 to 200. Lower values normally used if point data is accurate.
Maximum number of iterations	40	40 is adequate for both point and contour data.
Centering options	1	0- grid points at corners of cells 1- grid points at centres of cells
Elevation units	1	1-elevation in metres 2-elevation in feet
Grid size	100 m	

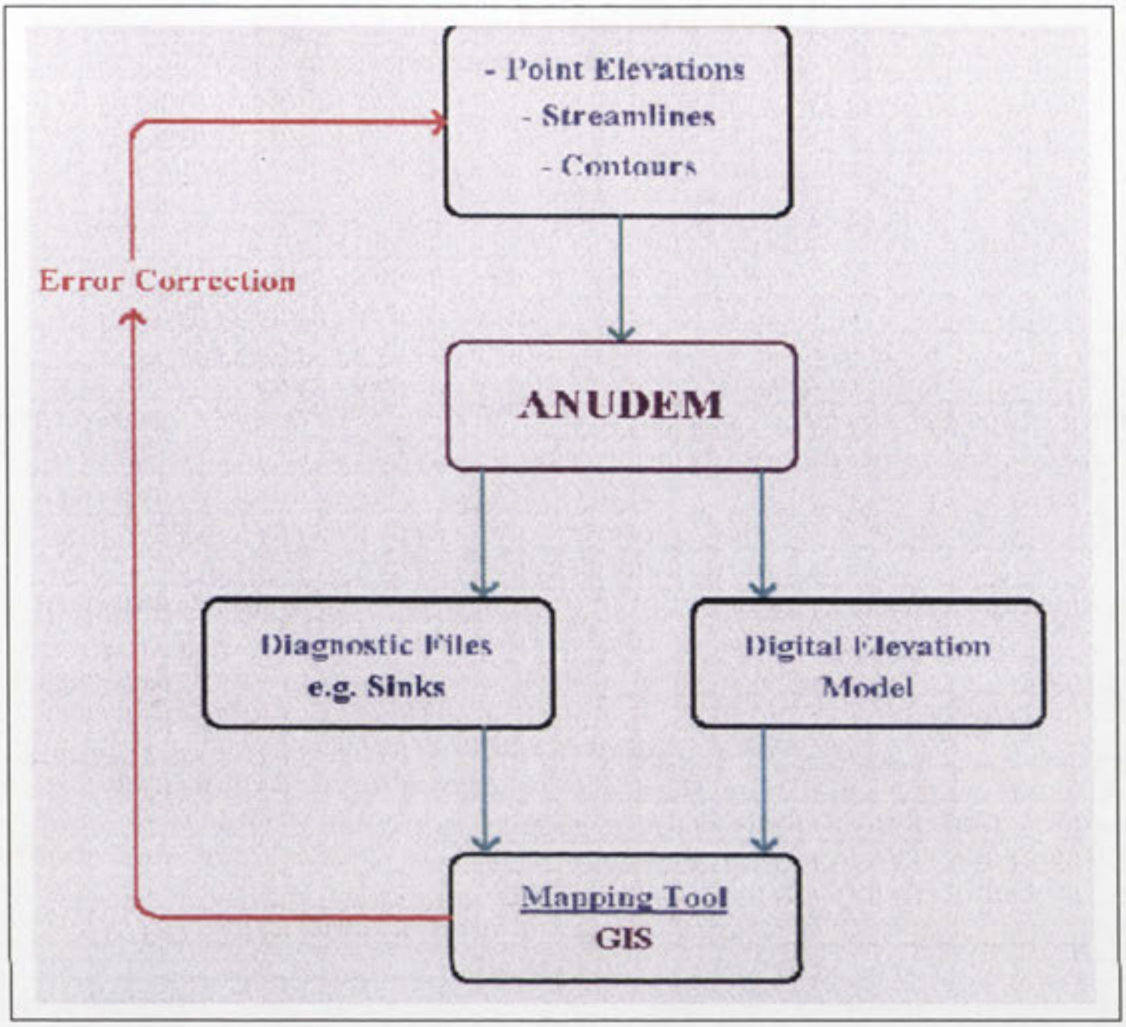


Figure 4.3 Characteristics of the ANUDEM Program (Hutchinson, 2002a).

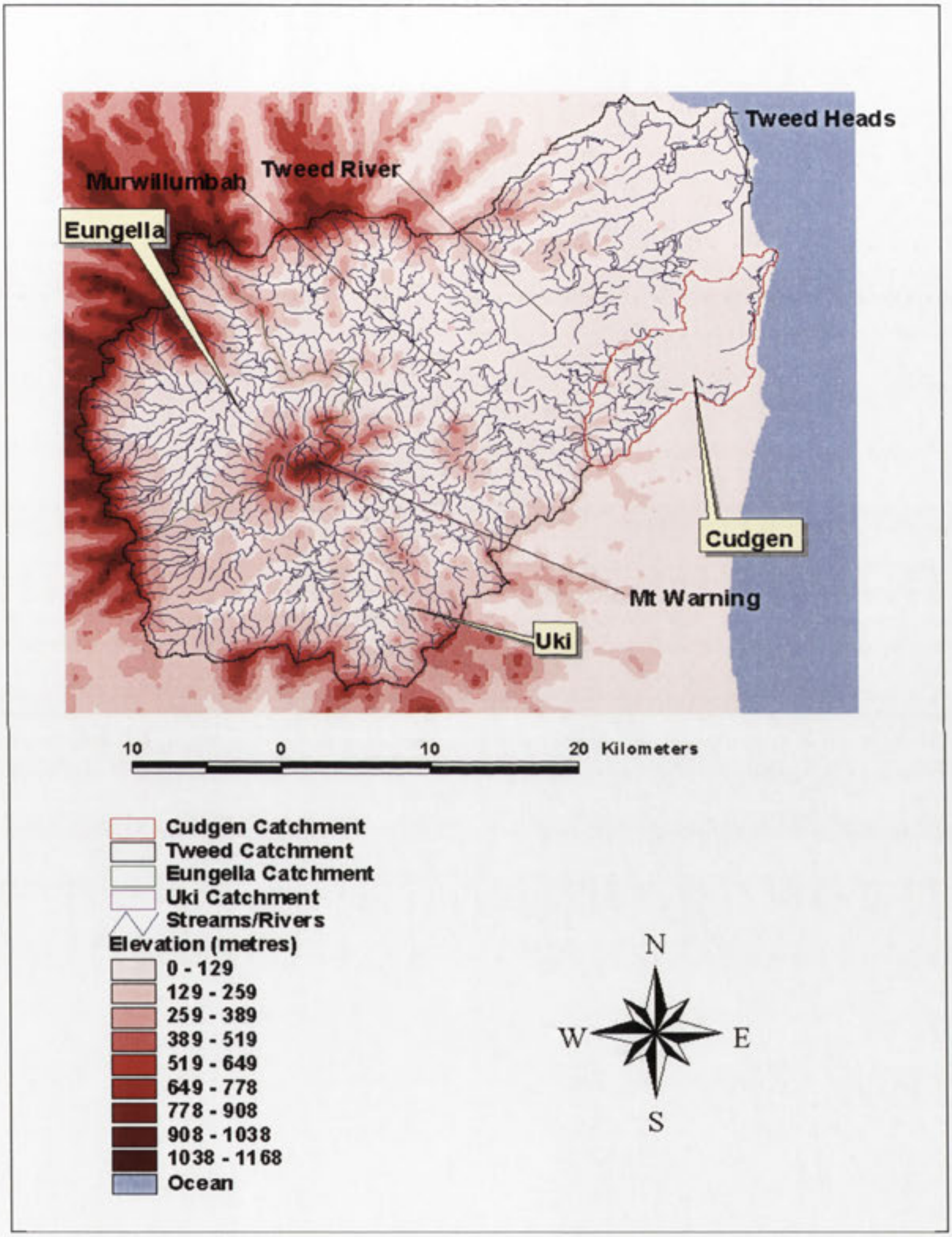


Figure 4.4. 100 metre DEM of the Tweed Catchment showing stream network and the three sub-catchments, Uki, Eungella and Cudgen. Mt Warning is the prominent land feature within the catchment.

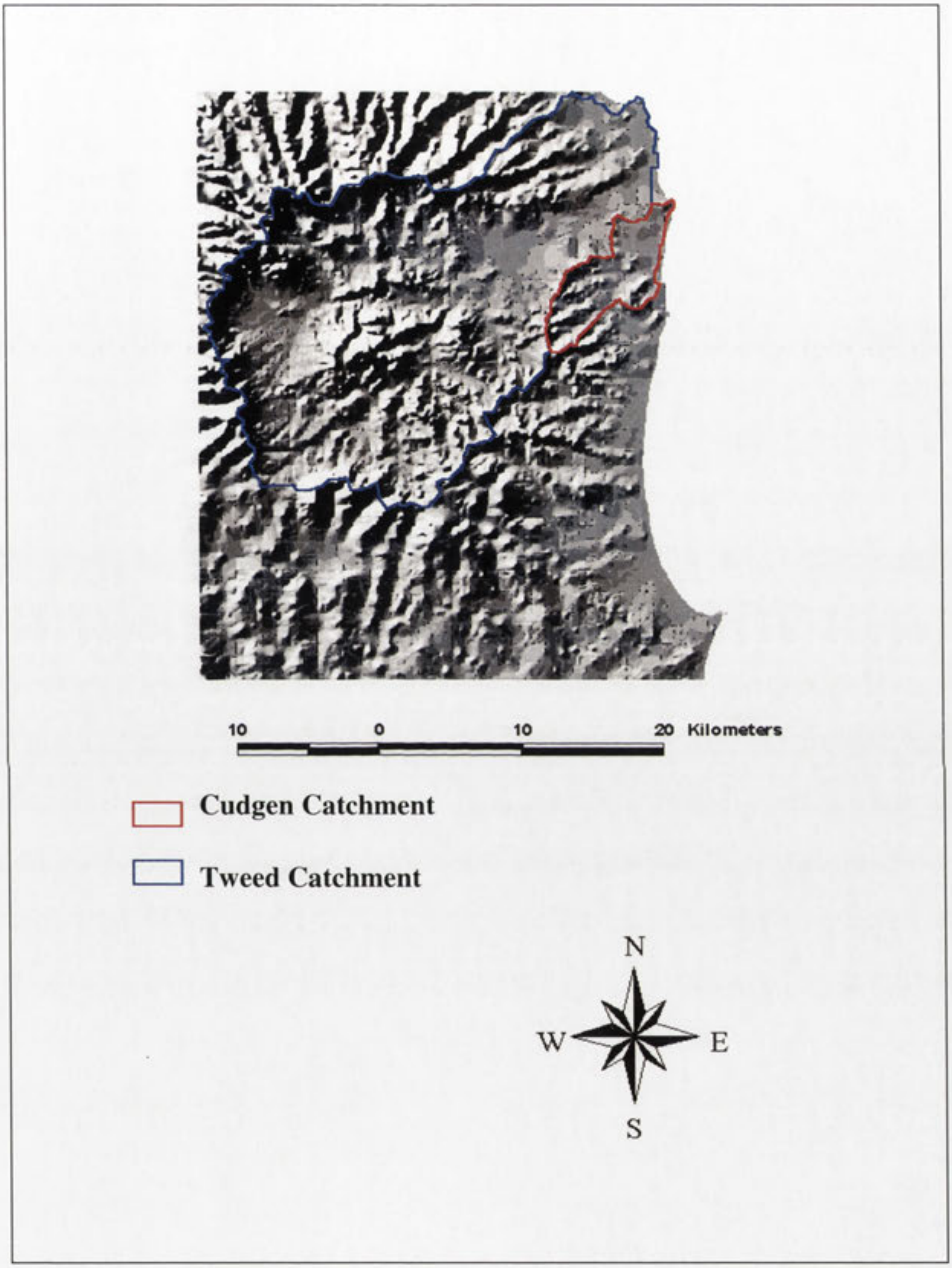


Figure 4.5 Shaded relief of the Tweed Catchment. The Tweed Basin is outlined in Blue and the Cudgen Sub-Catchment outlined in red. The Hillshade was derived from the 100 metre DEM.

Figure 4.6 A Three dimensional view of the Tweed Catchment looking west from the coastline. Mt Warning (centre) and the Tweed River (right). The 3 D view was derived from the DEM using the software Vistpro.

4.2.3 Development of a Precipitation Grid Using the ANUCLIM Program

The determination of spatially distributed monthly and annual climate means from climate data, is an important criterion for modelling ecological and hydrological phenomena. The procedures used here rely on streamflow and rainfall to predict runoff. Because rainfall is a spatially variable phenomenon, it is statistically more precise to use spatial rainfall data to predict runoff rather than using point data obtained from only one or two rainfall stations. Rainfall usually displays complex spatial patterns that are topographically dependent. Various methods have been used to spatially interpolate sparsely distributed point climate data. Interpolation is the estimation of a value of a variable between points of known values. It is possible to interpolate point climate data and present it spatially in the form of a climate surface map. There are two common statistical methods used for the interpolation of point climate data, namely kriging

(Delfiner and Delhomme, 1975) and thin plate smoothing splines. (Wahba and Wendelberger, 1980; Hutchinson, 1991).

Both methods use climate data observed at discrete locations to determine a simple formula that may be used to interpolate the point data. For n observed values Y_i at positions X_i, represented as coordinates in either a two or three dimensional euclidean space, it is assumed that:

$$Y_i = f\ (X_i) + e_i \qquad 4.4$$

Where $i = 1,\ldots.n$ and e_i is a zero mean error term. From equation 4.4, the function f is estimated from the observations Y_i and the error e_i is generally spatially discontinuous. For thin plate smoothing splines, $f\ (X_i)$ are values of a smooth unknown function at the data locations, whereas in the case of kriging, the $f\ (X_i)$ represent values of a spatially autocorrelated random field. Kriging works on the assumption that the associated spatial covariance function of the autocorrelated random field is stationary in that it is a function of separation only (Hutchinson, 1993). There are a few significant differences both practically and theoretically between the two methods. Hutchinson and Gessler (1994) provide a detailed description of these fundamental differences. Here we have chosen to use thin plate smoothing splines as implemented in the ANUSPLIN package (Hutchinson, 2002b) for the interpolation of point climate data. Wahba (1990) provides a comprehensive description on the technique of thin plate smoothing splines.

The development of a precipitation grid was based on the method of thin plate smoothing splines generated from sparsely distributed point rainfall data. The thin plate smoothing spline method is an extension or generalisation of the multivariate linear regression in which a suitably smooth non-parametric function is used in place of the parametric model. Thin plate smoothing splines works on the assumption that there is a spatial correlation between rainfall and elevation which varies according to latitude and longitude. The model can be represented as:

$$R_i = (X_i, Y_i, Z_i) + e_i \qquad 4.5$$

Where R_i is the square root of the rainfall observation, X_i is the latitude and Y_i is the longitude. Z_i is the elevation at the observed points and the e_i are zero mean normal random variables assumed to have a constant variance.

The ANUSPLIN program developed by Hutchinson (1991) was used to generate spline coefficients for rainfall surfaces for the Tweed Catchment for two separate time intervals, namely long-term interval (1921-1995) and short-term interval (1967-1998). The ANUCLIM program (version 5.0) (Holder *et al.*, 1999) was used to interrogate these climate surface coefficient files in point and grid format. Figure 4.7 shows the main features of the ANUSPLIN package. Since the number (N) of data points or rainfall stations used in the analysis was less than 2000, SPLINA was used to create the surface coefficient files. SPLINA is a Fortran 90 program used to fit partial thin plate spline surfaces to multi-variate noisy data. Data from a total of 552 rainfall stations were used in development of the spline rainfall surfaces for the Tweed. These stations are listed in Appendix A. In order to develop an accurate rainfall surface of the catchment, monthly and annual rainfall data from rainfall stations within a radius of 50km of the catchment boundary, were also used in the development of the rainfall surface.

ANUCLIM contains three programs, ESCOCLIM, BIOCLIM and GROCLIM, that enable the user to obtain estimates of monthly mean climate variables, including rainfall, evaporation as well as bioclimatic parameters, and indices associated with crop growth. These programs rely on climate surface coefficient files generated by ANUSPLIN. Surfaces for Australia, Canada, New Guinea and Africa have been developed (Holder *et al.*, 1999; Hutchinson, 1995). ANUSPLIN generates one climate surface file for each month of the year and can be used to estimate the long-term monthly mean rainfall. It is possible to generate surfaces for any region provided there are adequate meteorological data available. The spline surfaces normally used for Australia by ANUCLIM are based on long-term (1921-1995) monthly and annual rainfall averages derived from the Bureau of Meteorology.

The ANUCLIM program ESCOCLIM was used to produce annual and monthly rainfall grids for both the Tweed Catchment and Cudgen sub-catchment. ESCOCLIM generates output files consisting of climate variable estimates at specified locations. These locations can be presented either in the form of a regular grid or as a list of coordinates

(See Figure 4.8). The parameters from which climate variables are derived are determined for each point on a grid by providing ANUCLIM with a DEM of the catchment and the appropriate spline coefficient file. The coordinates and the UTM zone (56) for the Tweed Catchment were selected and the program allowed to run using the Tweed DEM created in section 4.2.2.

4.2.3.1 Developing a Precipitation Grid Using Short-Term Rainfall Records

It is possible to develop spatial rainfall surface grids for any time period within the last 80 years because of the availability of rainfall data from the Bureau of Meteorology. However, finding suitable streamflow data over such a considerable period was much more difficult because there are very few streamflow gauges operating in the Tweed Catchment. The only two fully operational streamflow gauges are located in the upper Tweed Catchment and both have a reliable history of streamflow data used to estimate runoff. One station is located on the Tweed River downstream from Uki and the other on the Oxley River, down stream from Eungella. To accurately estimate runoff from streamflow and rainfall, it was necessary to determine the mean spatial rainfall for the region upstream from the Uki and Eungella gauging stations. The geographical coordinates of these two stations were used to delineate the Uki and Eungella Sub-catchments using the DEM developed in section 4.2.2 and the flow accumulation method of Jenson and Domingue (1988). The delineation of the Uki and Eungella Sub-catchments allowed the mean spatial rainfall climate surfaces to be generated specifically for these catchments.

Based on records obtained from the NSW Department of Land and Water Conservation, (DLWC, 1998), there are reliable streamflow data for Uki and Eungella for the period 1967 to 1998. To create monthly rainfall surfaces for periods shorter than the time period 1921 –1995 or post 1995, it was necessary to create coefficient files specifically for these time periods. Rainfall data for the period 1967 to 1998 were used to generate surface coefficient files using the ANUSPLIN package. This time period was chosen to enable the determination of runoff coefficients derived from streamflow gauge results from the Uki and Eungella Sub-catchments for the same period. A fortran program was written to eliminate rainfall data records with less than five months of rainfall data. The program selected a total of 412 rainfall stations from the 552 used for generating surface coefficient files. From the monthly and annual climate rainfall surfaces, the monthly and annual mean spatial rainfall across the catchment, was determined for the two time periods discussed previously. The monthly values were then used to determine monthly runoff coefficients in section 4.2.6.

The final rainfall surface was created in ASCII Grid file format before it was converted to an ARC/INFO Grid coverage using the "ARCTOOLS conversion" program in ARC/INFO and then imported as a new theme to ARCVIEW. Apart from the short-term mean climate rainfall surfaces, monthly long-term (1921-1995) surfaces were also generated for the Uki and Eungella sub-catchments using the same methodology outlined in section 4.2.3.

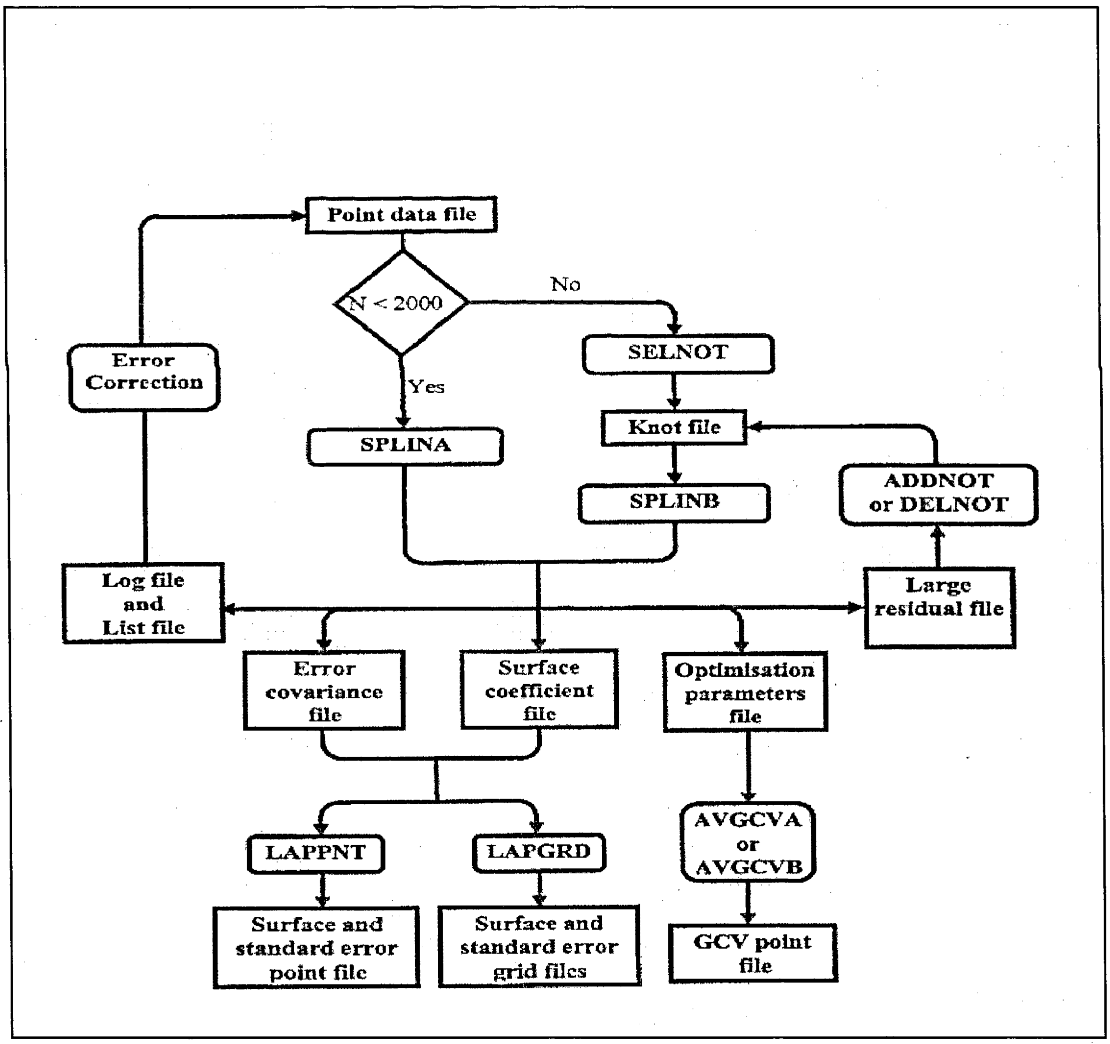


Figure 4.7 Components of the ANUSPLIN Package (Hutchinson, 2002b).

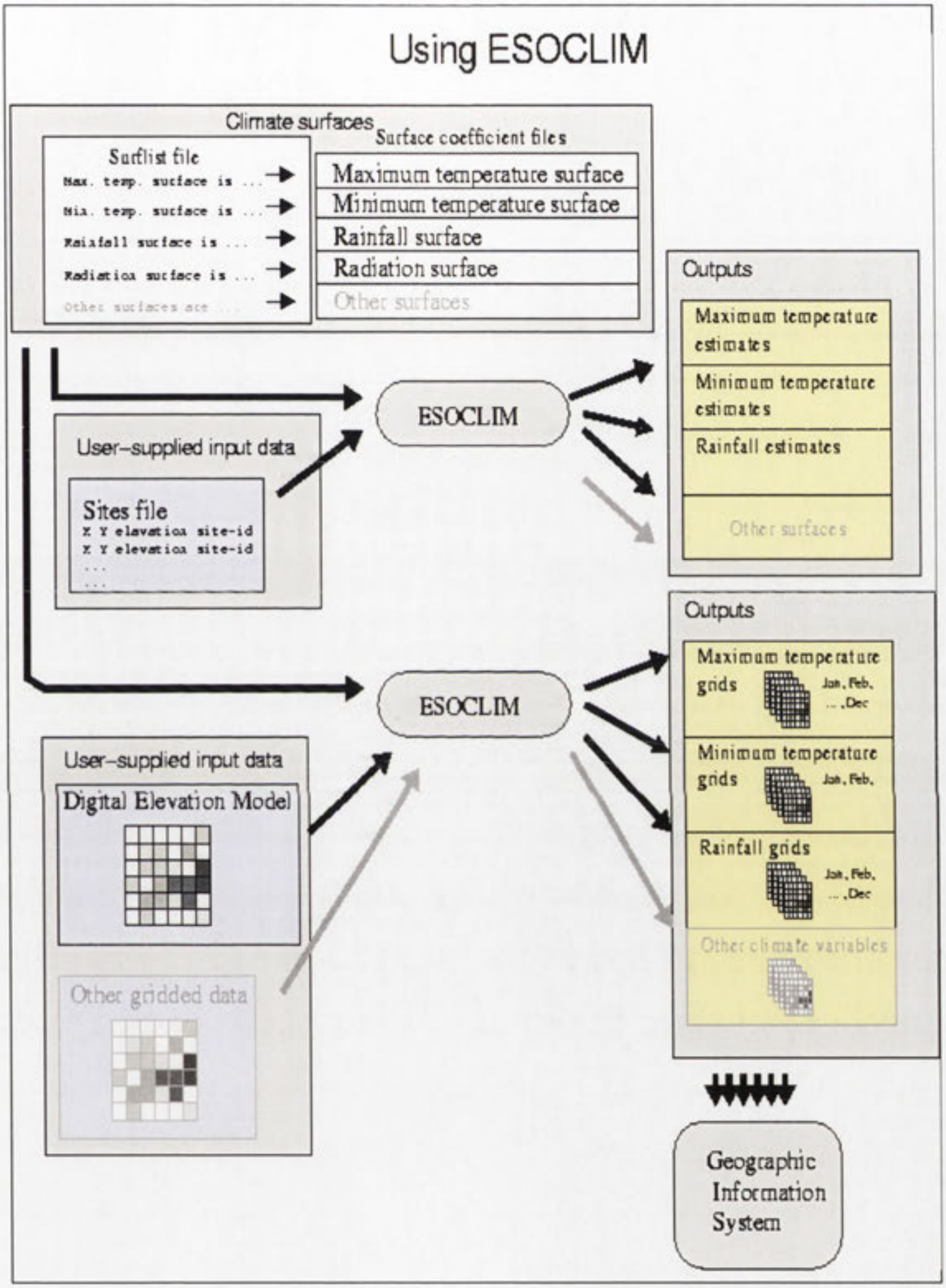


Figure 4.8 Characteristics of the ESCOLIM Program (Hutchinson, 2002b).

4.2.4 Analysis of Long-Term Rainfall Surfaces

The annual and monthly mean rainfall climate surface maps for the Tweed are shown in Figures 4.9 and 4.10 respectively. These rainfall climate surface maps were developed using the ANUSPLIN and interrogated by ANUCLIM based on long-term (1921-1995) monthly rainfall averages. The annual rainfall surface shows the annual spatial distribution in rainfall across the catchment. As expected, we find that the rainfall intensity is higher in the mountain ranges of the Caldera and Mount Warning. It is interesting to note, that the surfaces show a rain shadow to the west of Mount Warning which is apparent in all maps, regardless of the month. The amount of annual rainfall across the catchment varies from 1412mm to 3090mm. This is fairly consistent with previous rainfall studies by Eyre and Pepperell (1997), in which they had estimated that the Tweed Catchment receives an annual total of 3084 mm.

The long-term monthly rainfall surface maps reveal some spatial variation which is seasonally dependent. The coastal region (i.e, within 10 kilometres from the shore-line) of the Tweed Catchment has lower (spatially distributed) rainfall than the upper catchment during the summer months (December, January and February). However, this phenomenon is reversed during the autumn, and winter months in which the coastal region receives more rainfall than the upper parts of the catchment. This is particularly so for the month of May and August (Figure 4.10). There is significantly less rainfall during the winter months with the mean spatially distributed rainfall less than 100 mm during August and September.

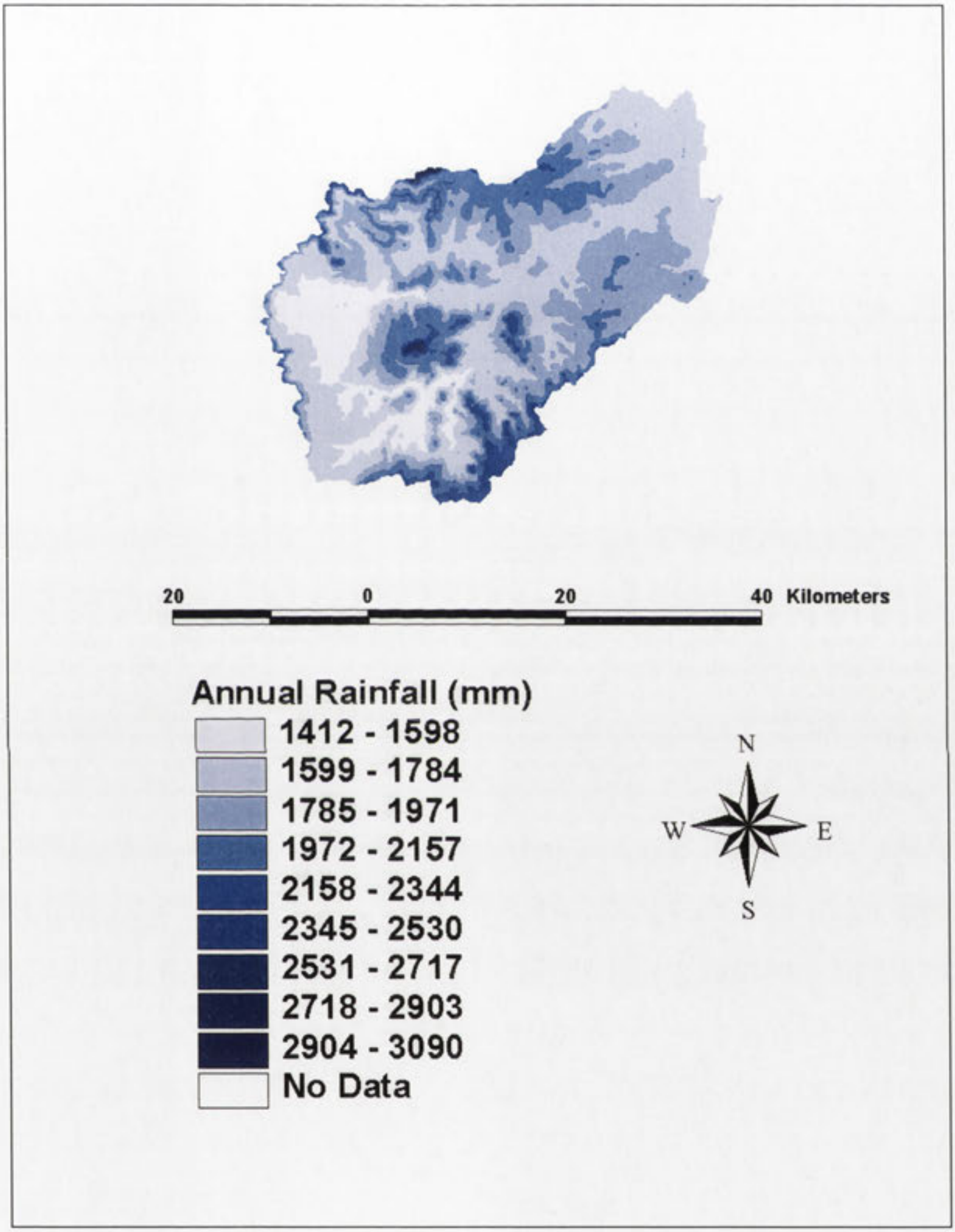
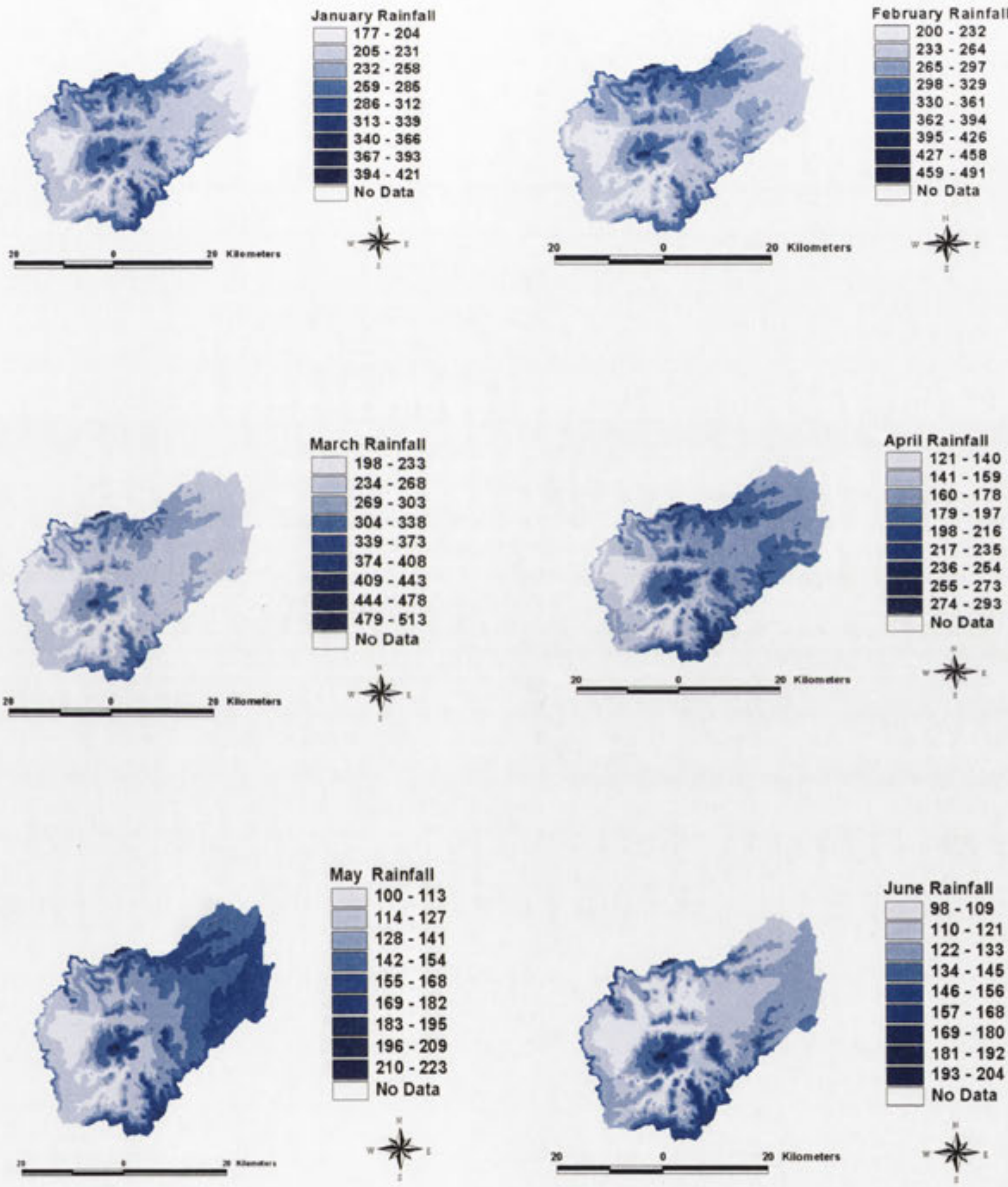
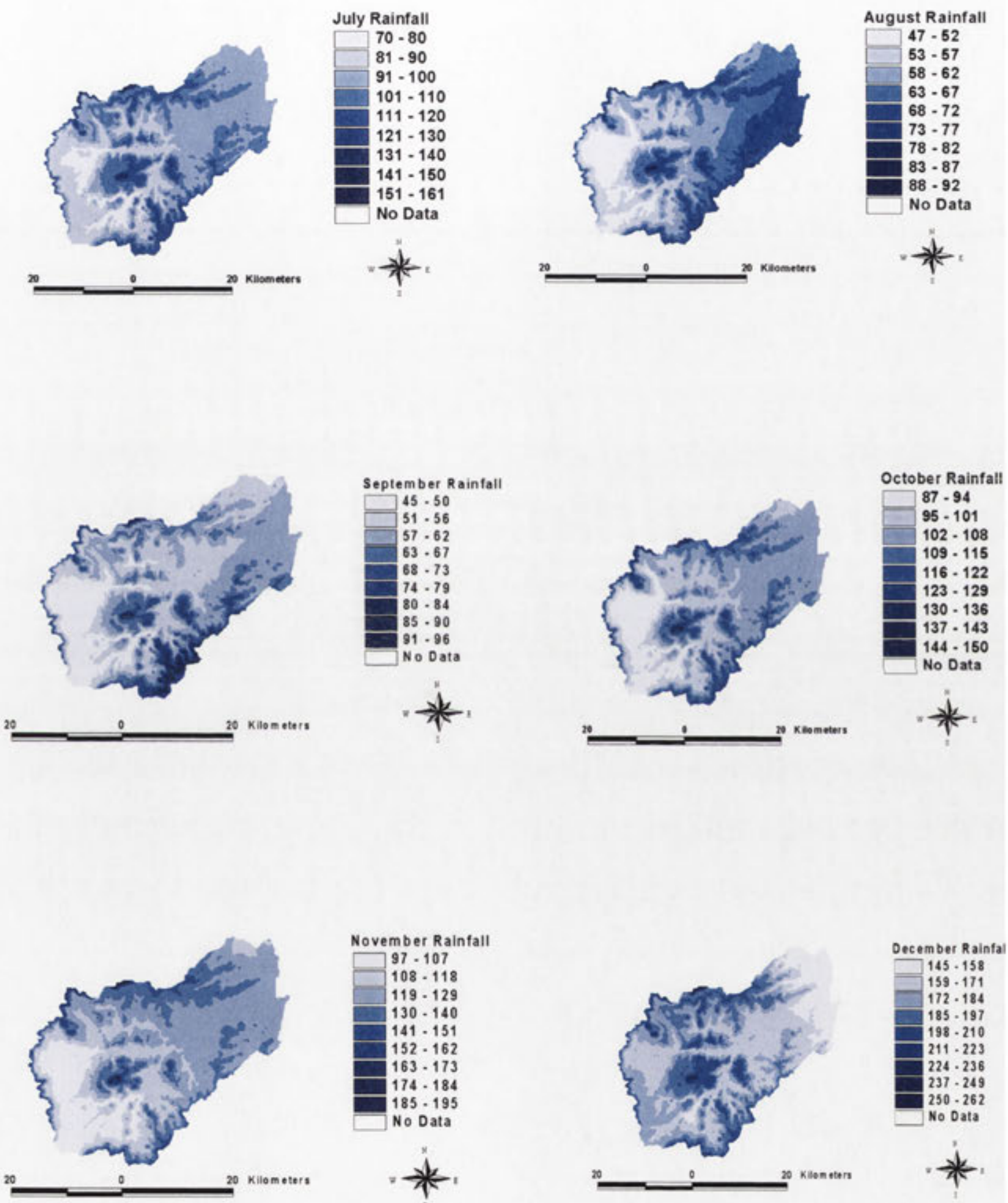


Figure 4.9 Spatial distribution of annual mean rainfall (1921-1995) for the Tweed Catchment.

Figure 4.10 Spatial distribution of monthly mean rainfall (mm)(1921-1995) over the Tweed Catchment.



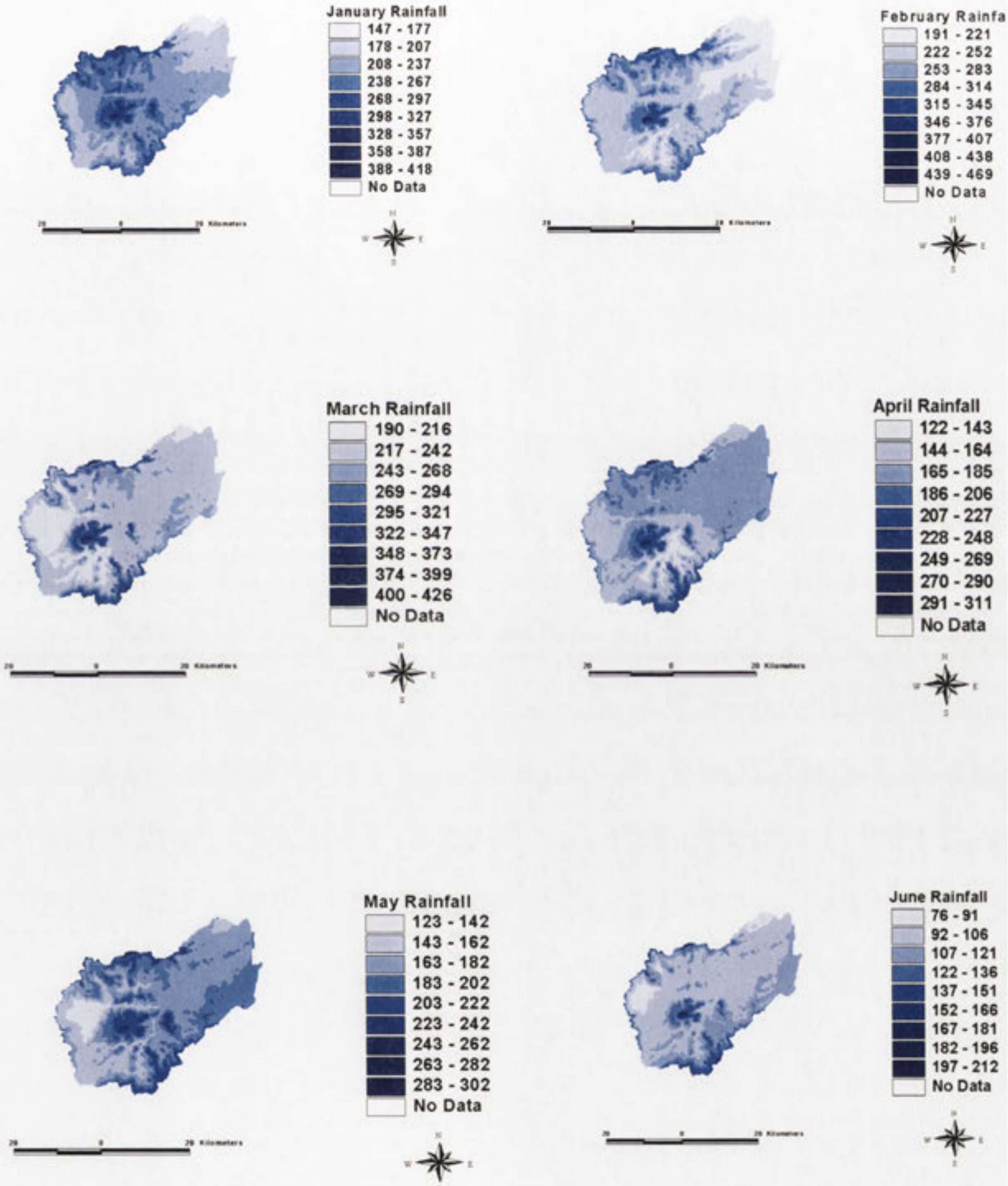

July Rainfall
70 - 80
81 - 90
91 - 100
101 - 110
111 - 120
121 - 130
131 - 140
141 - 150
151 - 161
No Data
20
0
20 Kilometers
August Rainfall
47 - 52
53 - 57
58 - 62
63 - 67
68 - 72
73 - 77
78 - 82
83 - 87
88 - 92
No Data
20
0
20 Kilometers
September Rainfall
45 - 50
51 - 56
57 - 62
63 - 67
68 - 73
74 - 79
80 - 84
85 - 90
91 - 96
No Data
20
0
20 Kilometers
October Rainfall
87 - 94
95 - 101
102 - 108
109 - 115
116 - 122
123 - 129
130 - 136
137 - 143
144 - 150
No Data
20
0
20 Kilometers
November Rainfall
97 - 107
108 - 118
119 - 129
130 - 140
141 - 151
152 - 162
163 - 173
174 - 184
185 - 195
No Data
20
0
20 Kilometers
December Rainfal
145 - 158
159 - 171
172 - 184
185 - 197
198 - 210
211 - 223
224 - 236
237 - 249
250 - 262
No Data
20
0
20 Kilometers

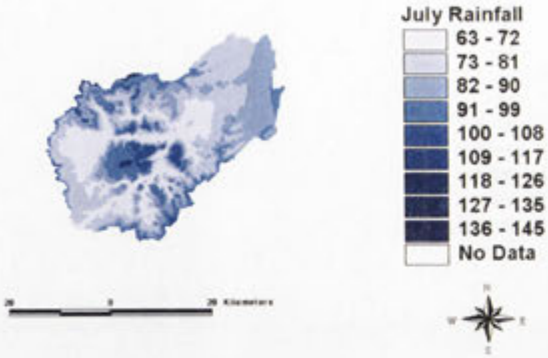
4.2.5 Analysis of Short-Term Rainfall Surfaces

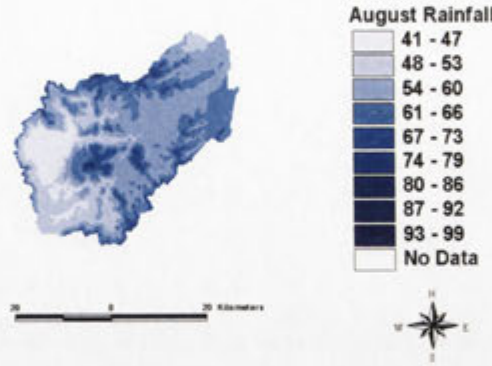
The monthly mean rainfall climate surface maps for the Tweed are shown in Figure 4.11. Unfortunately, to date, the ANUCLIM program only produces monthly surface coefficient files when using short-term rainfall records. However, it is possible to derive the annual mean spatial rainfall from the monthly mean rainfall values by summing the mean value for each month and dividing by the total number of months in the year. The annual mean spatial rainfall for the catchment from 1967 to 1998 (short-term) was 1814 mm. This is 6 mm less than the annual mean spatial rainfall for the Tweed from 1921 to 1995 (i.e, 1820 mm) which is not statistically different.

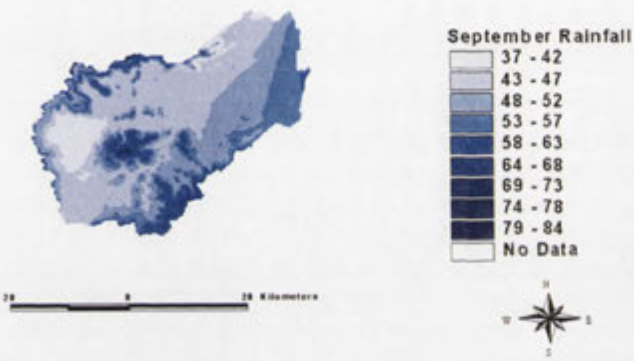
As with the long-term monthly rainfall surfaces, the short-term monthly surfaces also showed some spatial variation from month to month. This variation also appears to be seasonally dependent with higher spatially distributed rainfall in the upper catchment during December, January and February. The rainfall surfaces reveal that the lower catchment has higher spatially distributed rainfall during the winter and spring months (June to November) than during the summer months. It is interesting to note that the minimum and maximum monthly mean spatial rainfall results differ between the long-term (section 4.2.4) and short-term surfaces for certain months of the year.

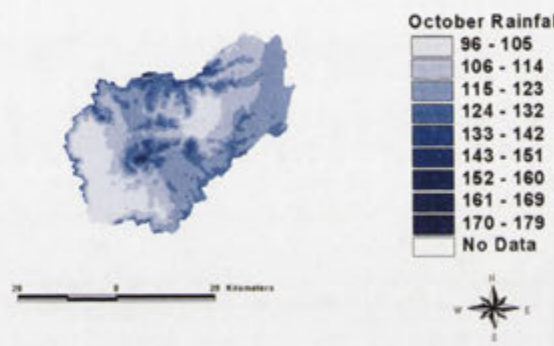
Figure 4.11 Spatial distribution of monthly mean rainfall (mm) (1967-1998) over the Tweed Catchment.

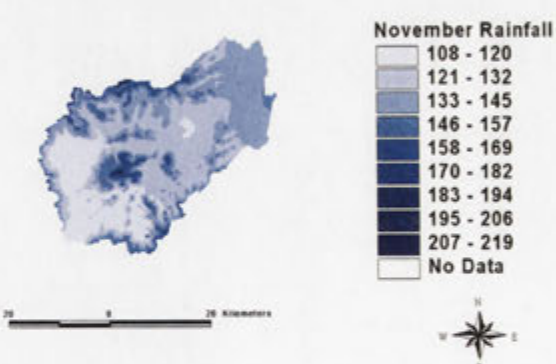


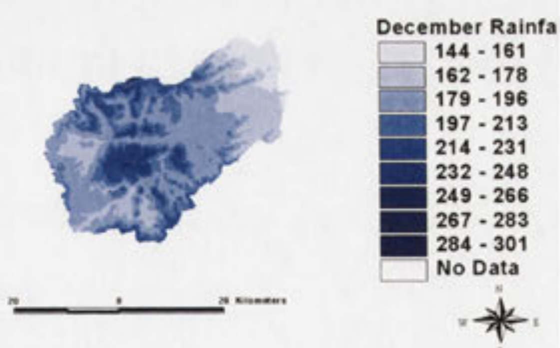

July Rainfall
63 - 72
73 - 81
82 - 90
91 - 99
100 - 108
109 - 117
118 - 126
127 - 135
136 - 145
No Data


August Rainfall
41 - 47
48 - 53
54 - 60
61 - 66
67 - 73
74 - 79
80 - 86
87 - 92
93 - 99
No Data


September Rainfall
37 - 42
43 - 47
48 - 52
53 - 57
58 - 63
64 - 68
69 - 73
74 - 78
79 - 84
No Data


October Rainfal
96 - 105
106 - 114
115 - 123
124 - 132
133 - 142
143 - 151
152 - 160
161 - 169
170 - 179
No Data


November Rainfall
108 - 120
121 - 132
133 - 145
146 - 157
158 - 169
170 - 182
183 - 194
195 - 206
207 - 219
No Data


December Rainfa
144 - 161
162 - 178
179 - 196
197 - 213
214 - 231
232 - 248
249 - 266
267 - 283
284 - 301
No Data

4.2.6 Investigation of Short and Long-Term Rainfall and Streamflow

Using the rainfall surface grids developed in sections 4.2.3 and 4.2.3.1 the mean spatial rainfall was determined for the Tweed Catchment and the sub-catchments of the Cudgen, Eungella and Uki. The monthly mean spatial rainfall for the long-term and short-term data, are shown in Figure 4.12 and 4.13 respectively. The mean spatial rainfall for the sub-catchments Uki, Eungella, Cudgen and the Tweed Catchment for long-term time interval was similar for all months except for May. The long-term results showed that on average the Cudgen received slightly more rainfall than the sub-catchments Uki and Eungella. Similarly, the analysis of the short-term time interval (1967–1998) (Figure 4.13) showed that across all four catchments the trend was similar. Although the sub-catchments Eungella and Uki are geographically different from the Cudgen, the results suggest that the mean spatial rainfall for the Eungella and Uki sub-catchments is fairly representative of the Cudgen sub-catchment and Tweed Catchment, based on both short-term and long-term data.

A comparison of the long-term (1921-1995) (Figure 4.12) and short-term (1967-1998) (Figure 4.13) spatial rainfall across the Tweed Catchment reveals a noticeable difference between the two time periods. Based on the long-term rainfall (1921-1995) the results suggest that for the period 1967-1998 the months May and December were wetter than normal and the months February and March were drier than normal. To obtain a better assessment of the difference between the two time periods, the standard error of the short-term Tweed Catchment rainfall was derived using the LAPGRD program in ANUSPLIN version 4.2 (Hutchinson, 2002b). LAPGRD calculates the standard errors using the estimated error covariance matrix of the spline surface coefficients fitted by SPLINA (See figure 4.7). Comparison of long-term (1921-1995) and short-term (1967-1998) monthly mean spatial rainfall for the Tweed Catchment and the standard error difference is shown in Table 4.2. We regard the difference between the short and long- term monthly mean rainfall as significant if the difference between the mean short-term rainfall and mean long-term rainfall is greater than 2.5 times the SE shown in table 4.2 (Hutchinson, personal communication, 2002). We can see from Table 4.2 that for the short-term rainfall the months February, March, June, July, August and September are significantly drier when compared with the long-term rainfall averages. Alternatively, the months May, October and December are significantly wetter when compared with the long-term rainfall averages. It should be mentioned that, although the standard error provides a good estimate of rainfall variability between the two time periods, it should not be used as the sole determinate in identifying significant differences in rainfall between time periods. Based on these results, a more detailed and separate investigation of rainfall variability in the Tweed was warranted and the results of this investigation are provided in Chapter 6. The variability between the long-term (1921 –1995) and short-term (1967 - 1998) rainfall, highlights the importance of ensuring that the analysis of rainfall and streamflow are representative of the same time periods - an essential element in rainfall-runoff modelling.

Both the mean spatial rainfall for long and short-term time periods, for the Cudgen, Uki and Eungella, revealed that the Cudgen Sub-catchment receives slightly higher rainfall during the winter months from April to August, with slightly lower rainfall during the summer months from December to March (Figure 4.12 and 4.13). Higher rainfall would be expected in the upper catchment during the summer months where elevation and higher summer temperatures would have a greater influence on the formation of storm clouds and precipitation. The rainfall climate surfaces for the Tweed Catchment (Figure 4.10 and 4.11) shows that precipitation is spatially different between the coastal regions and the upper catchment depending on the season.

The analysis of the mean annual spatial rainfall results, for all four catchments including the individual mean annual rainfall for point value data at Murwillumbah is shown in Figure 4.14. Both the short-term and long-term mean annual spatial rainfall results were similar for all four catchments. Out of all four catchments, Eungella recorded the lowest mean annual spatial rainfall result, for both long and short-term rainfall. This may be the result of a rainfall shadow effect due to Mt Warning, as discussed previously. There was a significant difference between the mean rainfall for Murwillumbah and the mean spatial rainfall. This clearly demonstrates that spatial rainfall data, as opposed to point data, from an individual rainfall station, provides a better representation of the amount of rainfall that falls across the catchment as a whole.

A comparison was also made between the streamflow (1967-1998) and the rainfall for both long-term and short-term time periods (Figures 4.15 and 4.16). The streamflow data for the Tweed Catchment was obtained from the NSW Department of Land and

Water Conservation (DLWC, 1998) and the analysis of the data (i.e calculation of monthly mean streamflow for the time period 1967-1998) was carried out using the software HYDSYS (marketed by Hydstra Pty Ltd, www.hydsys.com.au). Streamflow data from two gauging stations, Uki and Eungella, were used in the analysis.

As shown in Figure 4.15 the monthly mean streamflow at Uki reflects the monthly mean spatial rainfall for the same time period (ie 1967-1998), however, there is a strong discrepancy between the streamflow and long-term spatial rainfall for May (Figure 4.16) with rainfall being disproportionate to streamflow.

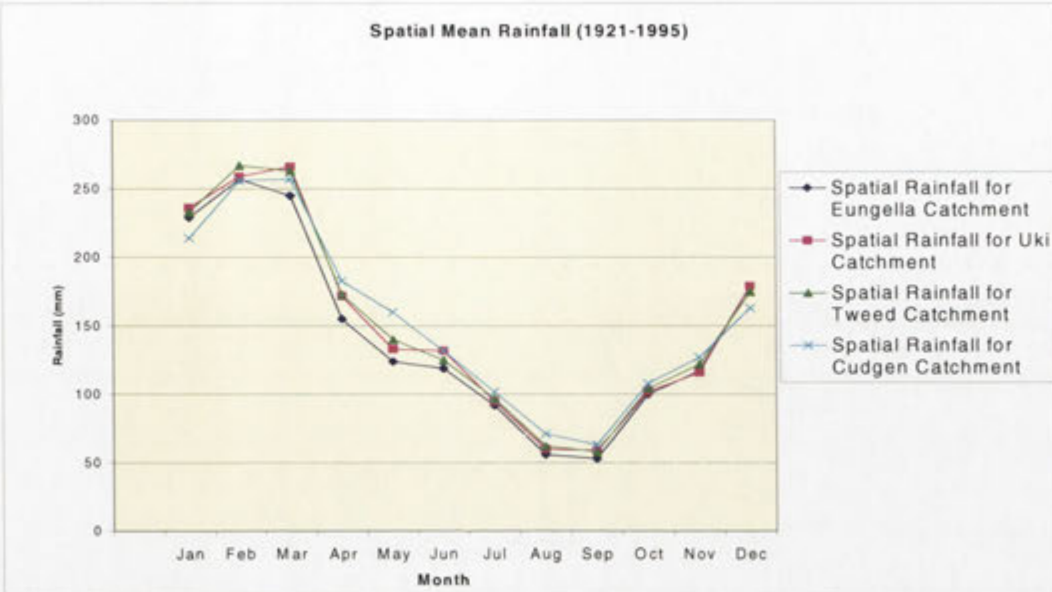


Figure 4.12 Spatial mean rainfall for Eungella, Uki, Cudgen Sub-catchments, and Tweed Catchment for the period 1921-1995.

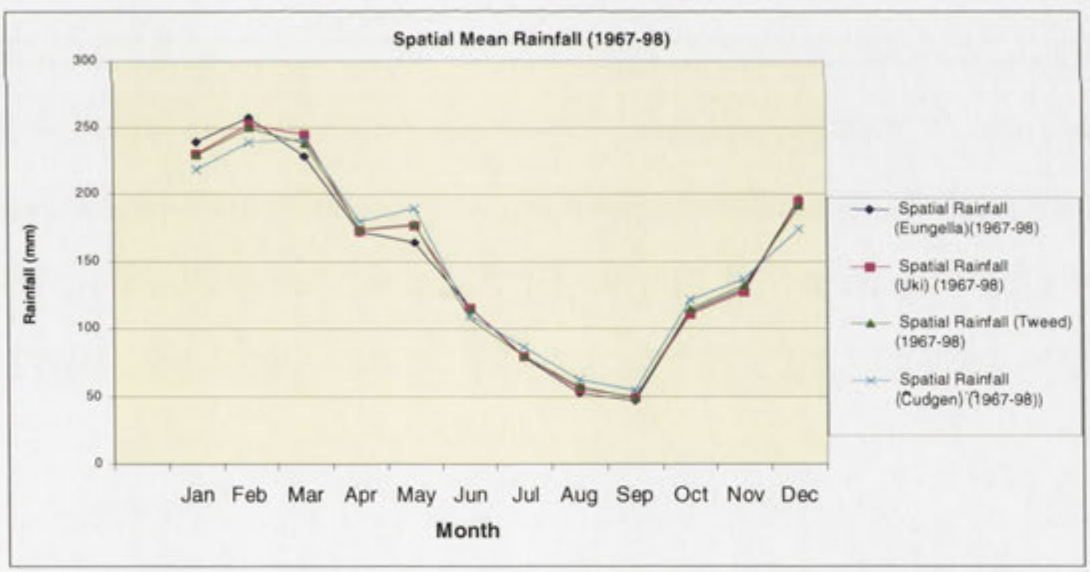


Figure 4.13 Spatial mean rainfall for Eungella, Uki, Cudgen Sub-catchments and the Tweed Catchment for the period 1967 to 1998.

Table 4.2 Comparison of long-term (1921-1995) and short-term (1967-1998) monthly mean spatial rainfall for the Tweed Catchment and the standard error difference for the short-term Tweed Catchment rainfall. We regard the difference between the short and long-term monthly mean rainfall as significant if the difference between the mean short-term rainfall and mean long-term rainfall is greater than 2.5 times the SE. Red asterisk indicates significant differences.

Month	Long-term monthly mean rainfall	Short-term monthly mean rainfall	Standard Error (SE) for short-term catchment rainfall	Comments
January	233	230	4.7	No difference
February	267	252*	4.0	Drier
March	263	245*	4.3	Drier
April	173	173	3.9	No difference
May	140	177*	3.4	Wetter
June	125	116*	2.4	Drier
July	97	80*	1.5	Drier
August	62	55*	1.1	Drier
September	58	50*	1.2	Drier
October	104	111*	2.6	Wetter
November	122	127	2.1	No difference
December	175	195*	3.1	Wetter

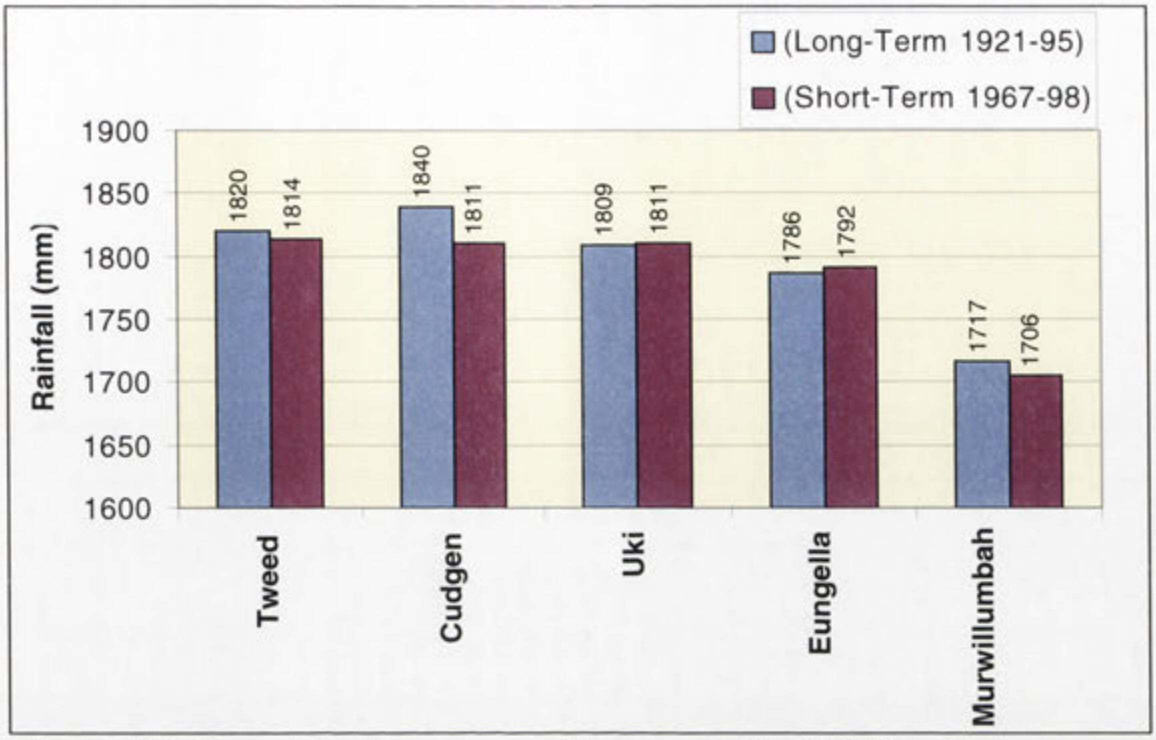


Figure 4.14 Comparison between annual mean spatial rainfall and annual mean rainfall (point data) at Murwillumbah for different catchments.

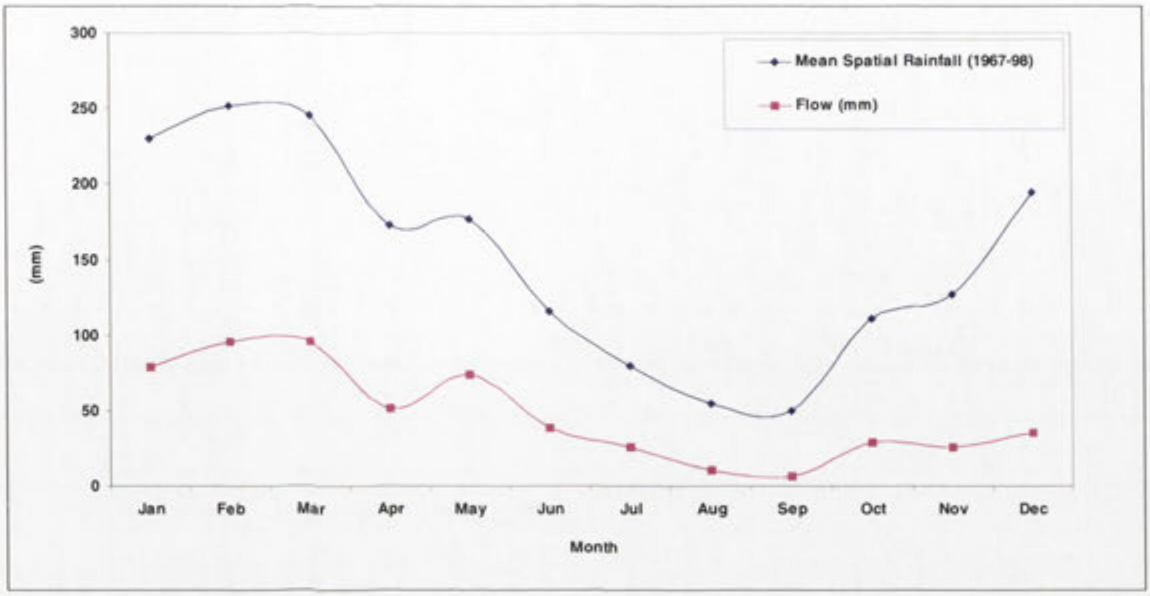


Figure 4.15 Comparison between short-term (1967-1998) spatial rainfall and flow (mm) at Uki (1967-1998) for the Tweed Catchment.

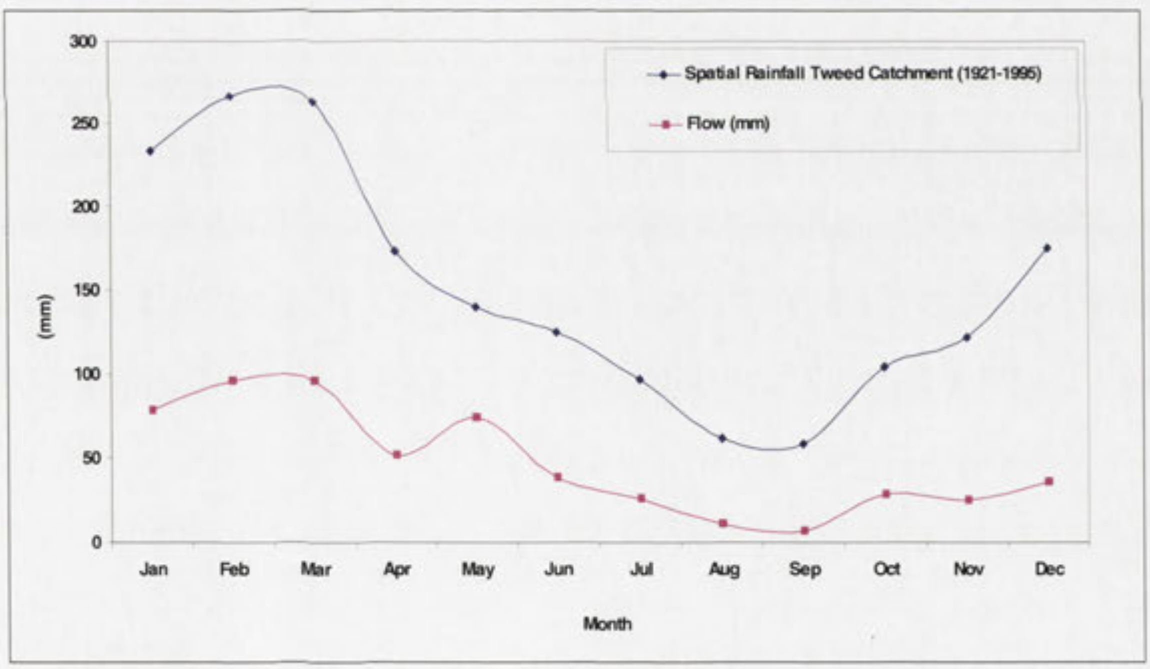


Figure 4.16 Comparison between long-term (1921-1995) spatial rainfall and flow (mm) at Uki (1967-1998) for the Tweed Catchment.

4.2.7 Determination of Monthly and Annual Runoff Coefficients

There are two main methods used for predicting runoff. These include:

1. Soil water balance determination.
2. Calculating the runoff coefficient derived from streamflow and rainfall data.

Computing a soil water balance is a conceptual method for determining runoff, whereas runoff coefficients are determined from comparing stream with rainfall statistics for similar periods. For the latter method, it is necessary to have access to streamflow and rainfall records. To determine soil water balance it is necessary to have information on the following parameters:

- Monthly or daily rainfall records.
- Actual evapotranspiration rates corresponding to the same time interval as rainfall.
- Water storage capacity of the soil.
- Groundwater discharge and recharge rates.
- Land use activities.

Unfortunately, catchment data, required to calculate a soil water balance equation for the Tweed is not available. It was therefore decided that the annual and monthly runoff coefficient could be estimated from rainfall and streamflow data for a particular period. As mentioned above, two suitable gauging stations with streamflow data were chosen to calculate annual and monthly runoff coefficients. These were the gauging stations at Uki on the Tweed River and the gauging station at Eungella on the Oxley River. The determination of annual and monthly runoff coefficients were derived using monthly mean spatial rainfall and streamflow results for the period 1967 to 1998. The mean spatial rainfall for the Uki and Eungella was previously determined in section 4.2.3.1 and the results of this analysis showed that based on short-term monthly mean spatial rainfall results, these two sub-catchments are fairly representative of the Tweed Catchment and the Cudgen Sub-catchment. Figure 4.17 also shows the similarity in the monthly mean spatial rainfall for the Uki and Eungella Sub-catchments between 1967 to 1998. Rainfall peaks during February and is at its lowest during September for both sub-catchments. Uki had slightly higher rainfall during March and May while Eungella receives slightly more rainfall than Uki during January and February.

Apart form having similar rainfall statistics, both catchments are also similar in area (274 km^2 for Uki and 218 Km^2 Eungella) with similar topography. Although significant regions of both catchments have in recent years been converted to grazing land (according to State Forests of NSW), large sections of the Uki and Eungella are still heavily forested (EIS, 1996).

The mean measured monthly streamflow for the sub-catchments Uki and Eungella is shown in Figure 4.18. The mean measured monthly streamflow was similar for both sub-catchments for the period 1967 to 1998. As an additional check of the data, a rainfall/runoff correlation was also carried out by graphing monthly mean rainfall and streamflow for each month of the year over the entire record (1967-1998).

The monthly runoff coefficient was derived from the monthly mean streamflow and the spatially averaged monthly precipitation for the Uki and Eungella Sub-catchments for the period 1967-1998. The spatially averaged precipitation and runoff coefficient were derived using equations 3.4 and 3.5 in section 3.1.2.1 (Chapter 3). The monthly runoff coefficient C_m is therefore defined as:

$$C_m = \frac{RO_m}{P_m} \qquad 4.6$$

Where RO_m is the observed monthly mean runoff and P_m is the spatially averaged monthly precipitation for the catchment expressed in mm. A linear regression analysis for runoff coefficient versus rainfall was carried out on both sub-catchments (Figure 4.19). A third linear regression analysis was also carried out using data from both catchments (Figure 4.20).

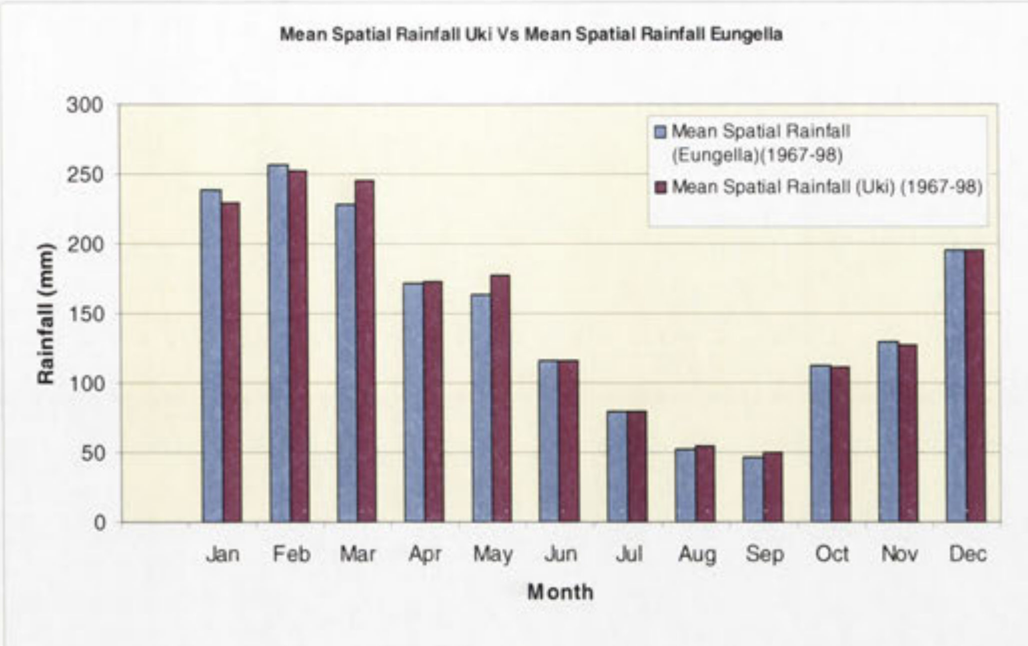


Figure 4.17 Comparison of monthly mean spatial rainfall for Uki and Eungella Sub-catchments for the period 1967-98.

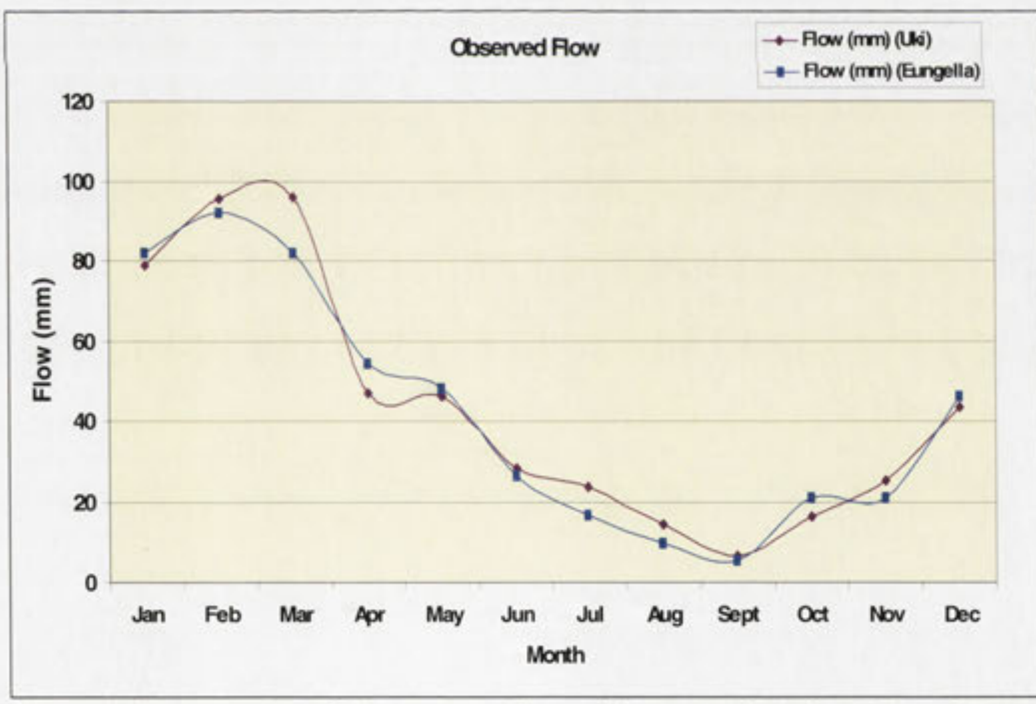
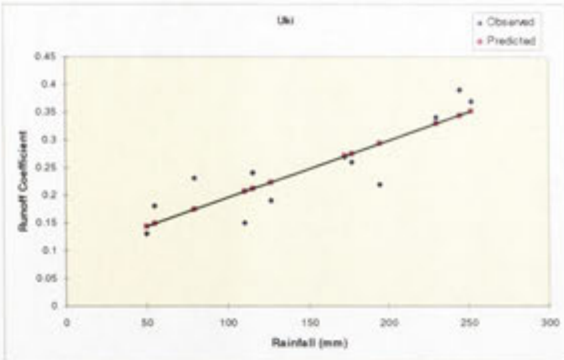
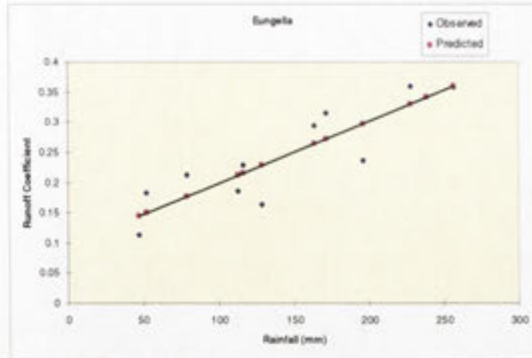


Figure 4.18 Comparison of the measured monthly mean flow for Uki and Eungella Sub-catchments for the period 1967-98.





(A) Y=0.092+ 0.00102x (R^2=0.87) ***(B) Y=0.096+ 0.00102x (R^2= 0.88)***

Figure 4.19 Linear Regression for Rainfall versus Runoff Coefficient for the sub-catchment of Uki (A) and Eungella (B), where for a given volume (mm) of rainfall (x) there is a corresponding runoff coefficient (y).

A linear regression for runoff coefficient versus mean rainfall (for all 12 months) was derived for the Eungella and Uki sub-catchments (Figure 4.19 A and B). The correlation coefficient squared of 0.87 and 0.88 was obtained for Uki and Eungella respectively. A combined regression for rainfall versus runoff coefficient was carried out using the results obtained for both catchments (Figure 4.20).

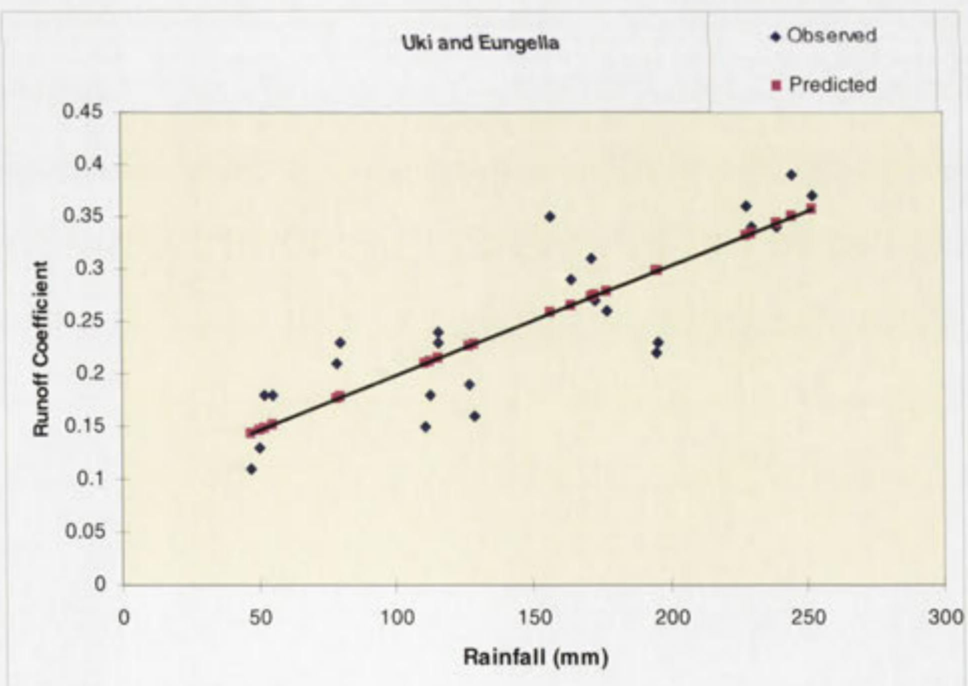


Figure 4.20 Linear Regression for Rainfall Versus Runoff for the Eungella and Uki combined. Y= 0.094+0.00104x (R^2= 0.84), where for a given volume (mm) of rainfall (x) there is corresponding runoff coefficient (y).

Therefore, the combined monthly C_m runoff coefficients were found to fit for the time period 1967 to 1998 are given as:

$$C_m = 0.00104P'_m + 0.094 \qquad (R^2 = 0.84) \qquad 4.7$$

The runoff coefficient derived for each month across the Tweed and its sub-catchments is shown in Figure 4.21. By using the linear regression function (equation 4.7), a runoff coefficient was also calculated for each month based on the long-term mean spatial rainfall records (1921- 1995) (Figure 4.22).

From these calculations it can be seen that all sub-catchments displayed similar runoff coefficients for each month. The monthly runoff coefficients are higher during the summer months (~0.35) and as low as 0.14 during late winter and early spring.

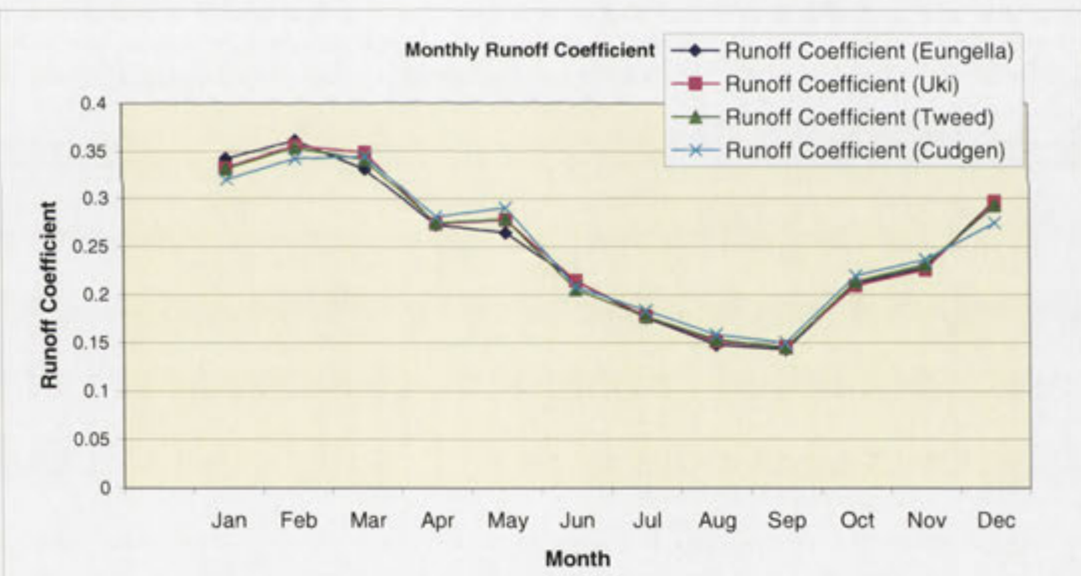


Figure 4.21 Monthly runoff coefficients for Eungella, Uki, Tweed and Cudgen Catchments. Runoff coefficients based on the mean spatial rainfall results for the period 1967-98.

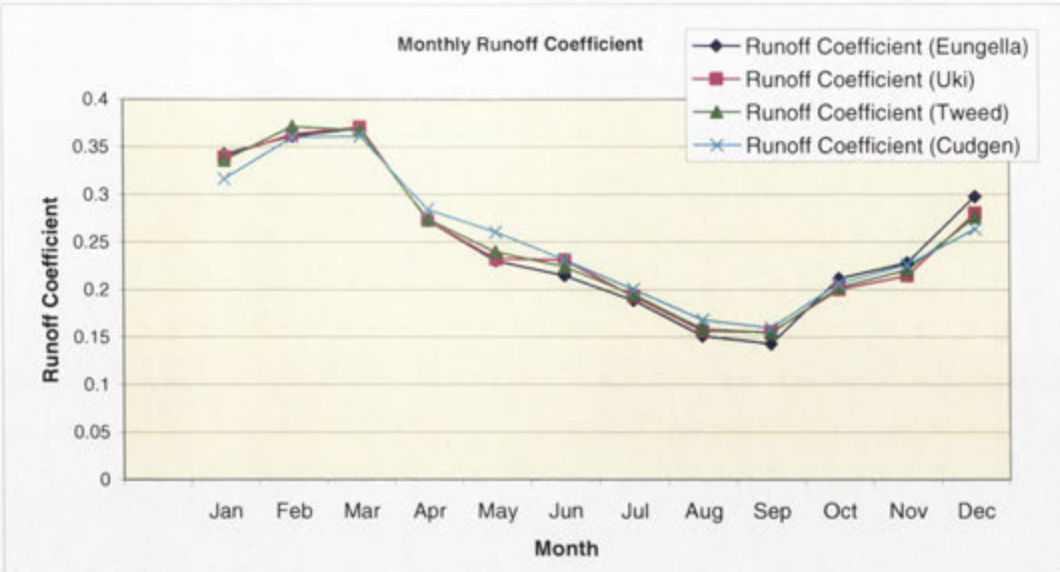


Figure 4.22 Monthly runoff coefficients for Eungella, Uki, Tweed and Cudgen Catchments. Runoff coefficients based on the mean spatial rainfall for the period 1921-95.

According to RACAC (1995) the Tweed Catchment experiences one of the highest annual runoff per square kilometre in NSW due to its high annual rainfall and small catchment size. They estimated that the runoff as a percentage of rainfall is as high as 33% with the average yearly discharge for the Tweed River above Uki of 158,387 ML/yr. The DLWC (1998) results showed that the observed annual flow at Uki was around 155,000 ML/yr. The observed flow for Eungella was less than the observed flow recorded at Uki at 125,381 ML/yr, but gave a higher runoff coefficient. The annual mean spatial rainfall and streamflow data (DLWC, 1998) for the Uki and Eungella Sub-catchments were used to calculate the annual runoff coefficient. Table 4.3 summaries the observed annual flows for the Uki and Eungella Sub-catchments and the mean annual spatial rainfall. These observed flows were based on data obtained from the DLWC (1998) and RACAC (1995).

Table 4.3 Comparison of annual runoff coefficients for the Tweed and Sub-catchments.

Catchment	Rainfall (mm)	Flow ML (Q)	Area (A)	Q/A	Runoff Coefficient
Tweed#	1650#	520,000#	1032	503	0.30
Uki	1814*	155,189+	274	566	0.31
Uki	1814*	158,387#	274	578	0.32
Eungella	1792*	125,381+	218	575	0.32

* Annual Mean Spatial Rainfall.

Predicted Annual Flow and Rainfall based on RACAC (1995) estimate (using discharge data from 1956 to 1995).

+ Observed Annual Flow DLWC (1998).

Based on the results summarised in Table 4.3 the annual runoff coefficient for Uki and Eungella is between 0.31 – 0.32. An annual runoff coefficient of 0.32 was used in modelling predictions.

4.2.8 Creation of an Annual Runoff Grid

The transportation of non-point contaminants into river networks and lakes is influenced by direct runoff which is a function of precipitation. Therefore, in order to model the flow of contaminants in surface waters, it is important to estimate runoff. Here the spatial distribution of runoff is calculated using the spatially dependent rainfall and the annual runoff coefficient.

The avenue script, rogrid.ave, developed at the University of Texas (Hellwege, 1996), was used to calculate the runoff grid for the catchment using the annual runoff coefficient determined in section 4.2.7. The annual precipitation grid developed in section 4.2.3 and the rogrid script were used to create the runoff grid. The avenue script rogrid.ave, operates in ArcView and computes a runoff grid (Figure 4.23) based on the runoff coefficient. An annual runoff coefficient of 0.32 was used in the calculation of the runoff grid.

The runoff grid shown in Figure 4.23 provides a view of the spatial distribution of runoff depth across the Tweed Catchment. Runoff depth varies from 450 to 990 mm across the catchment with lower runoff depths around the base of Mt Warning and the floodplain in the eastern sector of the catchment. Mt Warning the Caldera Ranges experience higher runoff depths (600-990mm) than the rest of the catchment due to the higher rainfall. It is interesting to note that the floodplain has slightly higher runoff depths (500-600mm) than parts of the catchment around the base of Mt Warning (450-500mm).

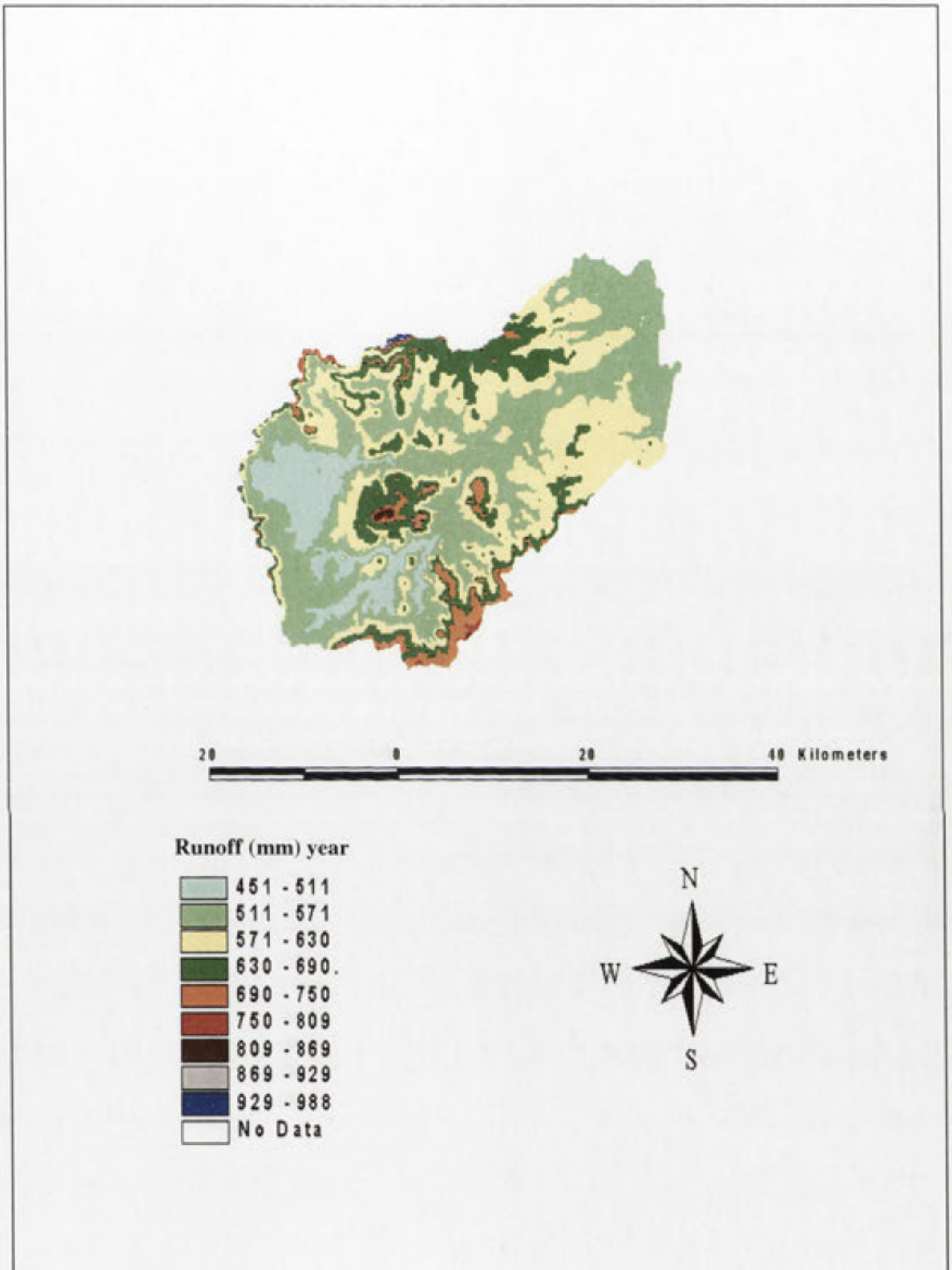


Figure 4.23 Runoff Grid calculated using the runoff coefficient and the avenue script "rogrid".

4.2.9 Preparation of Acid Sulfate Risk Map Data

Previous research has shown that the depth of sulfuric acid layers and distribution of the ASS can vary significantly from one location to another (Johnston, 1999). Wide variations in the actual acidity have also been reported for the Tweed Catchment (Smith, 1999a). Earlier estimates have suggested that around 10,000 hectares of the Tweed floodplain has pyritic soil down to a depth of 0.5 metres with average pyrite concentrations around 3.5% (Creagh, 1991). Hayes (1993) provided estimates of ASS in the backplain and backswamps which he claimed were only around 30 cm deep in places. An estimation of the PASS for the Tweed River Valley can be derived from 1:25 000 topographical maps by mapping the extent of floodplain below the 10 metre contour line. The formation of PASS would have been favourable below this elevation during a sea-level rise, which proceeded the last glacial period. This method suggests the maximum area of PASS for the Tweed Catchment is around 19,000 hectares (Wilson, 1995).

These estimations are not capable of identifying oxidation which has resulted from either human activity or through watertable lowering. With many regions of the NSW coast undergoing rapid urban and rural development, there was clearly a need to provide relevant information in an easily accessible format on the distribution and location of ASS. The need to accurately identify the location, distribution and the depth of the ASS layer in coastal low-lands is an important issue for land mangers and developers. This is particularly important in regions where there has been minium disturbance of PASS and where remediation strategies can be clearly aimed at preventing further oxidation by land use activities. More detailed surveys have been conducted by the Department of Land and Water Conservation as part of the Acid Sulfate Soils Risk Mapping program (Naylor *et al.*,1995; Naylor *et al.*, 1998).

The Department of Land Water Conservation (DLWC) under the Acid Sulfate Soil Risk Mapping Program prepared a series of coastal acid sulfate soil risk maps, which predict the distribution of acid sulfate soil derived from an assessment of the geomorphic environment (Naylor *et al.*, 1998). The assessment was confined to those areas where ASS are most likely to be found in coastal regions, for example, coastal floodplains up to 10 m Australian Height Datum (AHD); and used limited fieldwork that examined the relationship between landform, elevation and the occurrence of ASS. As part of the fieldwork, soil samples were also collected and analysed in the laboratory as further verification of the existence of ASS in those areas surveyed in the assessment. The landform components were the basic mapping unit used in the survey. The maps are acid sulfate soil risk maps and were not designed to provide site specific information on acid sulfate soils. They do not take into account detailed variations in the distribution and nature of ASS. In addition, actual and potential acid sulfate soils were not mapped separately.

These maps form the basis of Local Government Environment plans and are used extensively by Local and State Government authorities to help avoid further disturbance of acid sulfate soils through land development and drainage mitigation works. The risk maps were prepared by using NSW Land Information Centre 1:25 000 topographic maps as a starting point, with each risk map corresponding to the same name as the topographic map. Risk maps have been prepared for the entire east coast of NSW, South Australia and parts of Queensland.

4.2.10 Use of ASS Map Key

To identify accurately the probability of occurrence of acid sulfate soils, a map classification key has been developed by the Department of Land and Water Conservation. This classification key corresponds to a map class description based on the depth to the acid sulfate soil material, the environmental risk associated with disturbing the soil and the typical landform types. The map class description is based on four classes these include high probability of occurrence, low probability of occurrence, no known occurrence and disturbed terrain. A high probability of occurrence, includes those Holocene landform elements where the geomorphic processes have been suitable for the formation of ASS. A low probability of occurrence would include those environments that were at one stage unfavourable for ASS formation. A majority of these landform types are often Pleistocene in age.

An important factor to note from the ASS map key is the depth to the ASS layer. The closer the layer is to the surface, the higher the environmental risk. The depth to the ASS layer is dependent on the elevation of the site and subsequent alluvial deposits. Shades of colour are used on the risk maps to identify the depth at which the ASS layer is likely to be found. From the key, it is possible to determine the environmental risk associated with the area of interest. For example, ASS that have been identified as either bottom sediments, near or at the surface of the ground, or within 1 metre of the surface of the ground, are considered to be of high environmental risk. In these areas the construction of shallow drains, dams and foundations is therefore likely to pose high environmental risks.

The map classification scheme also provides an assessment of risk associated with land use activities. Figure 4.24 is a schematic cross-section of a levee to a backswamp showing the typical landform codes, depth of ASS material, land use activities and the associated environmental risk. Table 4.4 provides a description of each landform code for the Tweed Catchment, the depth of ASS layer and the associated risk factor, while Figure 4.25 shows the landform codes and how they relate to their location within the Tweed floodplain.

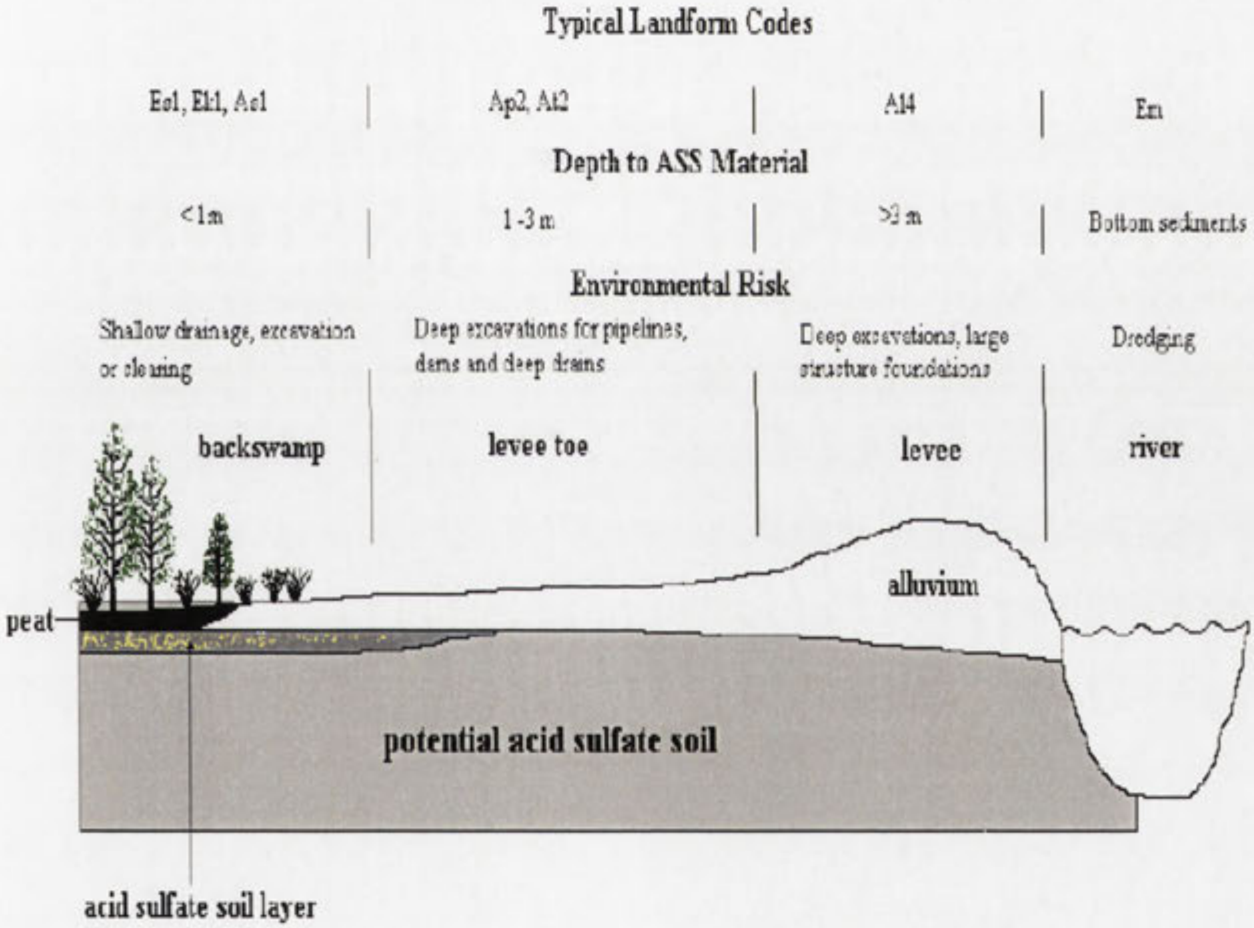


Figure 4.24 is a schematic cross-section of a levee to backswamp landform and the possible land use activities that can cause an environmental risk (Source: Naylor et al., 1998).

Table 4.4 Landform codes and their description.

CODE	HECTARES	Description	Depth to ASS	Risk Factor
B	6	beach		nil risk
HAk1	1	alluvial backswamp	1 metre	nil risk
HAl2	11	alluvial levee	2 metres	low risk
HAl4	3	alluvial levee	4 metres	nil risk
HAn1	4	alluvial channel	1 metre	nil risk
HAp1	28	alluvial plain	1 metre	high risk
HAp2	14	alluvial plain	2 metres	medium risk
HAp4	1	alluvial plain	4 metres	nil risk
HEa1	6	estuarine sandplain	1 metre	high risk
HEc	5	estuarine tidal creek		nil risk
HEi0	33	estuarine intertidal flat		nil risk
HEk1	2	estuarine backswamp	1metre	nil risk
HEm	6	estuarine bottom sediments		nil risk
HEn0	1	estuarine channel		nil risk
HEs1	7	estuarine swamp	1metre	nil risk
HEu1	12	estuarine supratidal flat	1metre	nil risk
HWa2	5	aeolian sandplain	2metres	nil risk
HWd2	5	aeolian dune	2metres	nil risk
LAk2	3	lacustine alluvial backswamp	2metres	nil risk
LAk4	1	lacustine alluvial backswamp	4metres	nil risk
LAl2	1	lacustine alluvial levee	2metres	nil risk
LAl4	7	lacustine alluvial levee	4metres	nil risk
LAn2	2	lacustine alluvial channel	2metres	nil risk
LAp2	18	lacustine alluvial plain	2metres	medium risk
LAp4	10	lacustine alluvial plain	4 metres	nil risk
LWa1	1	lacustine aeolian sandplain	1metre	nil risk
LWa2	3	lacustine aeolian sandplain	2metres	nil risk
NWd4	1		4metres	nil risk
O	81	nil		nil risk
OCEAN	5	ocean		nil risk
X2	21	disturbed terrain	2metres	nil risk

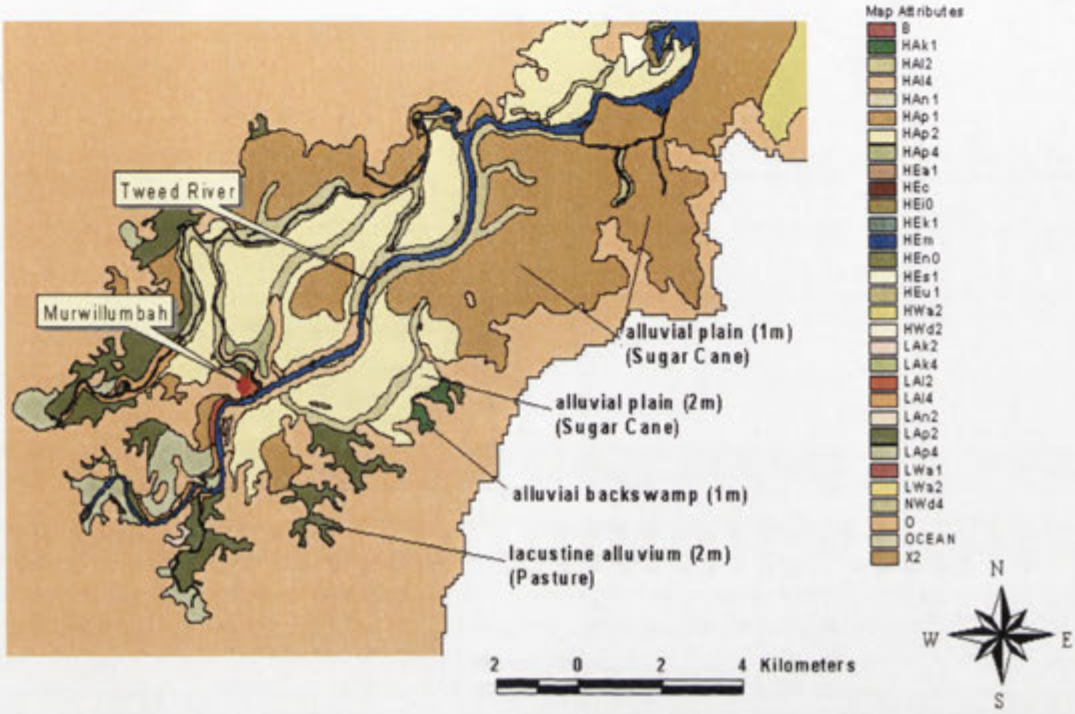


Figure 4.25 Geomorphology Landform Codes for the Lower Tweed floodplain used to ascertain the level of environmental risk associated with land use activities. The map description for each code is given in Table 4.4.

4.2.11 Development of a Risk Map Classification Scheme

For simplicity, the map class description categories, outlined in section 4.2.10, have been assigned a probability ranking of High, Medium or Low environmental risk, based on the probability and depth of ASS occurrence. For landform codes Es1, Ek1 and As1 with a depth of less than one metre to the ASS layer, there is a "High or Severe" environmental risk associated with most land use activities, ranging from shallow drainage to deep excavations. Similarly, the landform codes Ap2 and At2 with a depth to the ASS layer of 1 to 3 metres, have a "Medium or Moderate" level of environmental risk. Deep excavations for pipelines, dams and deep drains are considered hazardous for these regions. These classification have been used to develop a new polygon map feature in Figure 4.26, classifying the regions within the catchment as being either High, Medium or

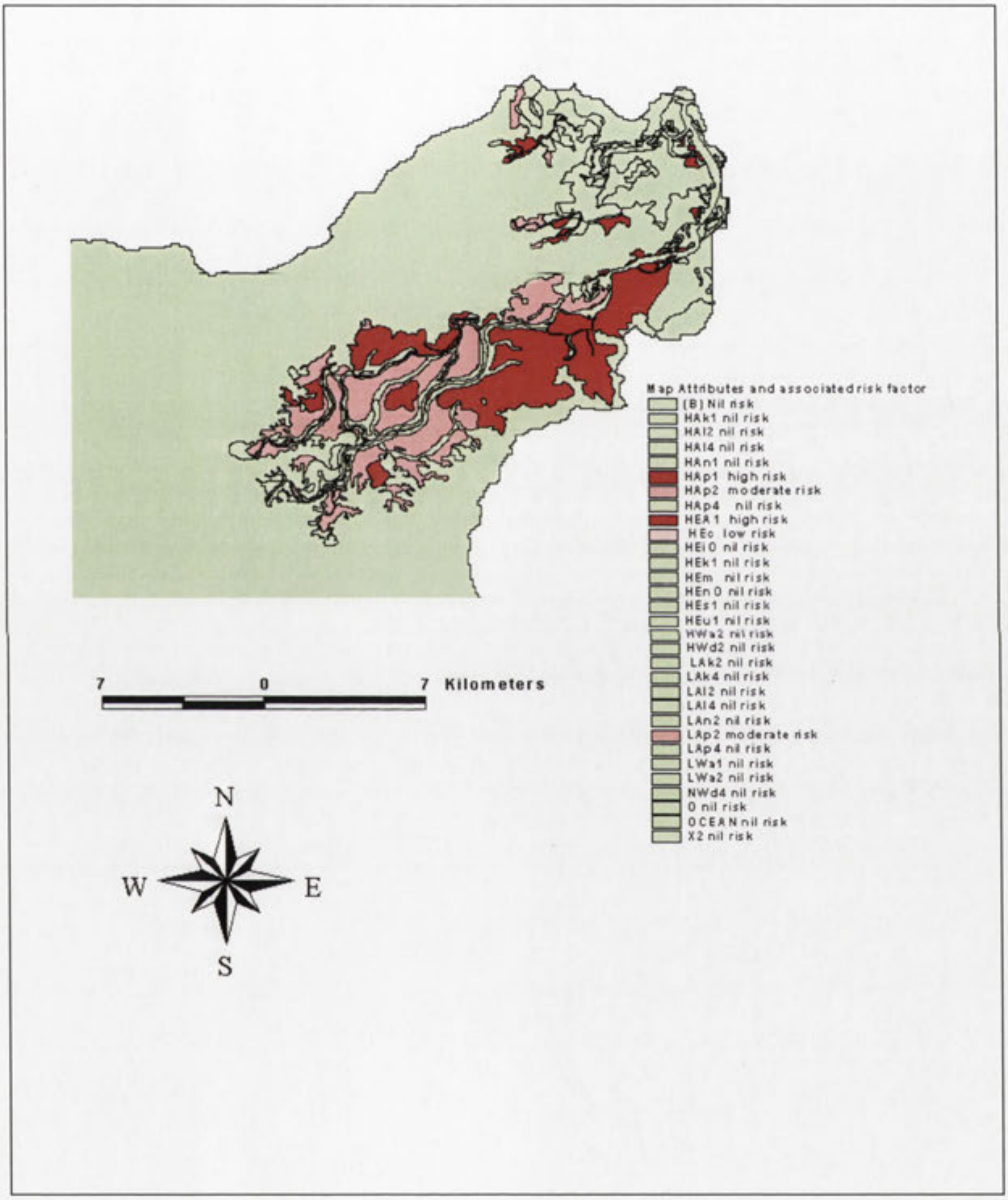


Figure 4.26 A new polygon map feature classifying the regions within the catchment as High, Moderate or Low environmental risk. Only the eastern section of the catchment containing ASS is shown.

Low environmental risk. The land form code (HAp1) represents alluvial plain and (HEa1) estuarine sandplain with the depth of ASS to one metre. These landform codes are regarded as having a high risk factor. Similarly, (HAp2) is alluvial plain and (LAp2) lacustine alluvial plain with depth of ASS material down to 2 metres. These two landform codes are regarded as moderate risk. The landform code (HAI2) is an alluvial levee with acid sulfate soil to a depth of 2 metres is low risk.

4.2.12 Development of a Surface Flow Direction Grid

An important requirement for modelling surface flow paths and for catchment delineation is the development of a surface flow direction grid, upon which drainage directions are assigned, to each grid cell in the DEM (Costa-Cabral and Burges, 1994). The question most frequently asked is - how accurate are digital elevation models in representing the features that have important hydrological significance in a catchment? There are several principal methods used for determining the drainage matrix from a DEM. The D8 method is the simplest and most commonly used (O'Callaghan and Mark, 1984; Costa-Cabral and Burges, 1994). The eight direction pour method, or D8 method, takes the filled DEM and calculates the direction of flow for all the grid cells. Each cell drains into the neighbouring cells with the steepest downhill descent (Figure 4.27).

According to Holmgren (1994), there are four basic assumptions concerning flow directions when dealing with hydrological modelling using the D8 method. The first assumption is that water naturally flows in the steepest direction of descent. The second assumption is that when water is flowing from one grid cell to another it is uniformly distributed within each grid cell. The third assumption treats all eight flow directions as equally prone to receiving runoff. The final assumption is based on the understanding that no runoff can take place from a lower grid cell to a higher grid cell, despite the possibility that regions within a lower grid cell may have elevations higher than the highest neighbouring grid cell. This occurs when the resolution of the DEM is low in comparison to the various landforms or when there is a small slope gradient involved, such as in coastal floodplains.

Based on these assumptions, the D8 method is somewhat restricted when examining variations of flow paths within the DEM. Some methods attempt to get around this problem by introducing a stochastic component or algorithm into the D8 method

(Rho8)(Quinn *et al.,* 1991). To determine the true flow distribution over a landscape, Holmgren (1994) examined the use of a weighted flow distribution parameter based on slope gradients to produce a multi-directional flow grid.

The use of a multiple flow direction algorithm may provide a better indication of runoff prediction in response to slope or hillside gradient, but the D8 method provides a better estimate of producing flow responses once the flow has reached the permanent drainage system (Quinn *et al.,* 1991). For the modelling carried out in this thesis, it was not necessary to model the distribution of runoff on hillslopes. Rather, the emphasis was on determining the total flow routed into the stream and stream network and not on the rate of runoff in response to slope. The ANUDEM program has the option of creating a surface flow direction grid when fitting the DEM (See Stein *et al.,* 1998). ANUDEM also incorporates directed streamline data (Figure 4.28) to produce flow paths of higher quality, especially in areas of low relief, than would otherwise be achieved through simply allocating the direction of steepest descent. This is an attractive feature of the ANUDEM program, considering the floodplain location of coastal acid sulfate soils.

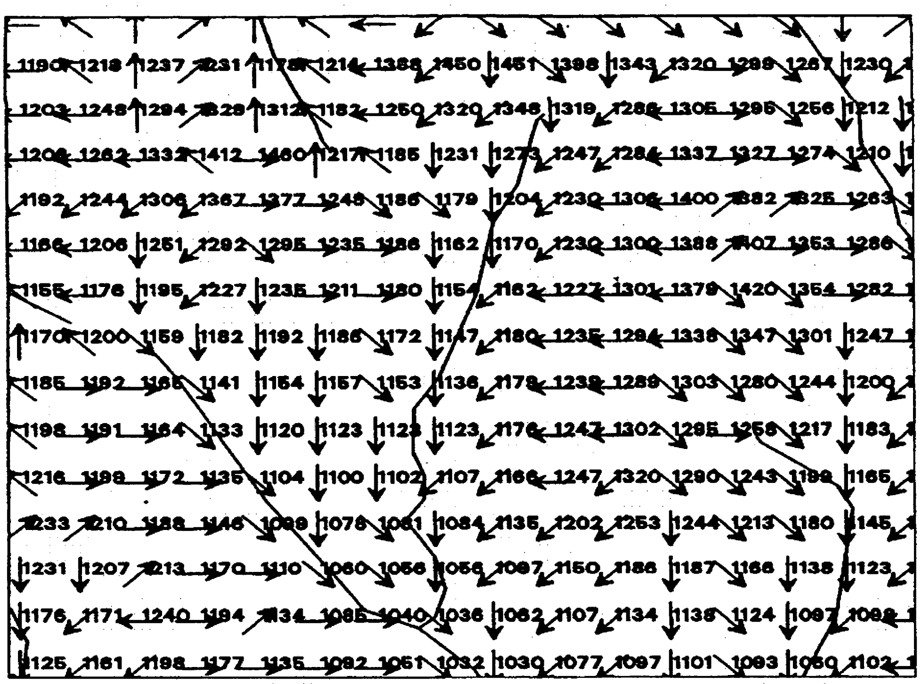


Figure 4.27 The D8 method of flow for identifying flow paths. The values are elevation points and the arrows represent the assigned flow direction. The ANUDEM program also incorporates information derived from directed stream data and imposed side conditions, however, this information may not always adhere to the D8 method of steepest descent. (Adapted from Stein et al.,1998).

The D8 method and directional streamline data (AUSLIG, 1992), were used to produce a flow direction grid from the DEM. Figure 4.27 shows the direction of flow (indicated by the arrows) assigned to each elevation point within the DEM. Only one elevation value can be assigned to each grid cell. The direction of flow can only be assigned to one direction, the direction of steepest descent. Since the ANUDEM program also uses the information provided by the directed streamline input data, flow directions may not always adhere to the rule of steepest descent.

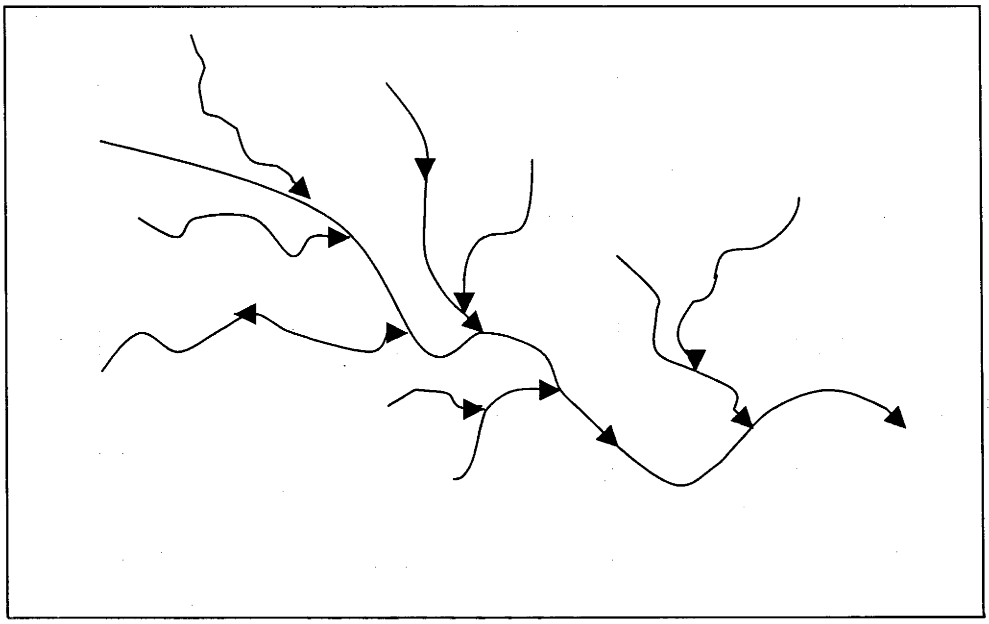


Figure 4.28 Flow directions produced by ANUDEM also incorporate information from directed streamline input data as shown above.

A flow Direction ASCII Grid file was created using ANUDEM before it was converted to a grid in an ARC/INFO environment and imported to Arc/View as a theme. ARC/INFO automatically assigns standard codes to indicate the direction of surface flow (See Figure 4.29). Figure 4.30 shows the D8 flow direction grid for the Tweed Catchment.

32	64	128
16		1
8	4	2

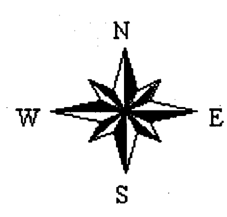


Figure 4.29 Standard ARC/INFO codes for flow direction. A flow in a westerly direction is given a value of 16 and an easterly flow is given a value of 1. A south-easterly direction is assigned a value of 2, and so on. A value of 255 is assigned to a cell with no flow direction (i.e sink).

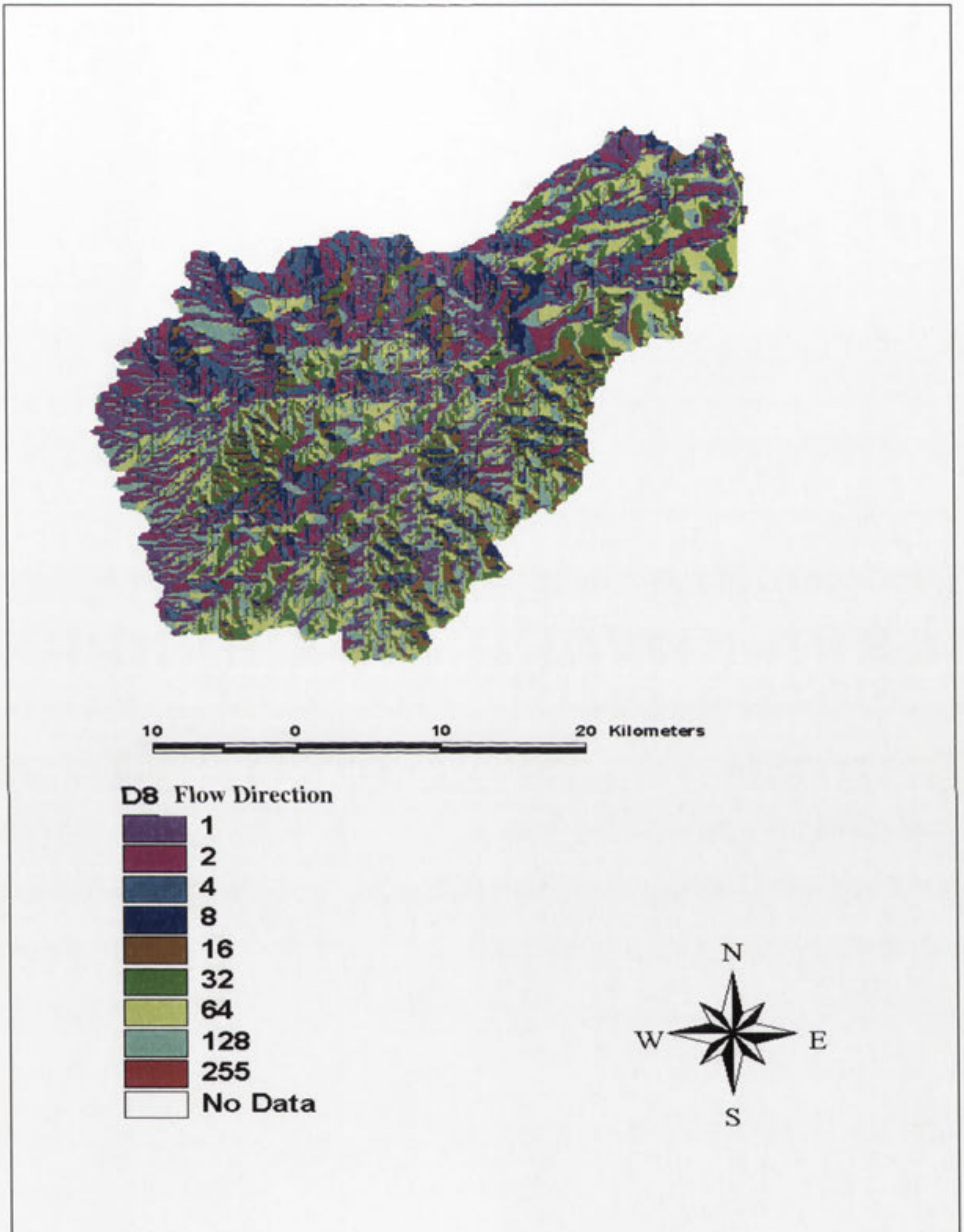


Figure 4.30 D8 Flow Direction Grid for the Tweed Catchment. A value of 255 indicates no direction (i.e sink).

4.2.13 The Weighted Flow Accumulation Function

A standard flow accumulation counts the number of cells upstream from each cell in the grid whereas a weighted flow accumulation sums the grid values by using a second grid known as the weighted grid. For example, a runoff grid such as the one developed in section 4.2.7 contains runoff values that are converted to runoff accumulation values. A weighted flow accumulation is calculated using the flow direction grid to count the number of cells upstream from each cell in the grid.

The model uses two types of weighted flow accumulation grids. The first involves a weighted flow accumulation using the runoff grid (weighted grid) and the surface flow direction grid developed in section 4.2.12. The resulting grid allows for the determination of the accumulated streamflow at any point in the catchment. The second weighted flow accumulation, uses the land loads grid as the weighted grid to predict the location of surface water loads. The resulting two grids can then be used to predict acid surface water concentrations. Therefore by using the flow accumulation function it is possible to predict the annual or monthly streamflow as well as acid surface water concentrations and acid loads at various locations throughout the catchment.

4.2.13.1 Development of a Weighted Runoff Flow Accumulation Grid

To compare the observed streamflow against the predicted streamflow it was necessary to develop a weighted flow accumulation grid which can then be used to predict streamflow at various locations within the stream network. The weighted flow accumulation was calculated using the ARC/INFO program and the command line function:

(*Grid: Runoffaccumulation* = flowaccumulation (Flow Direction Grid, Runoff Grid)).
The weighted runoff accumulation grid is shown in Figure 4.31.

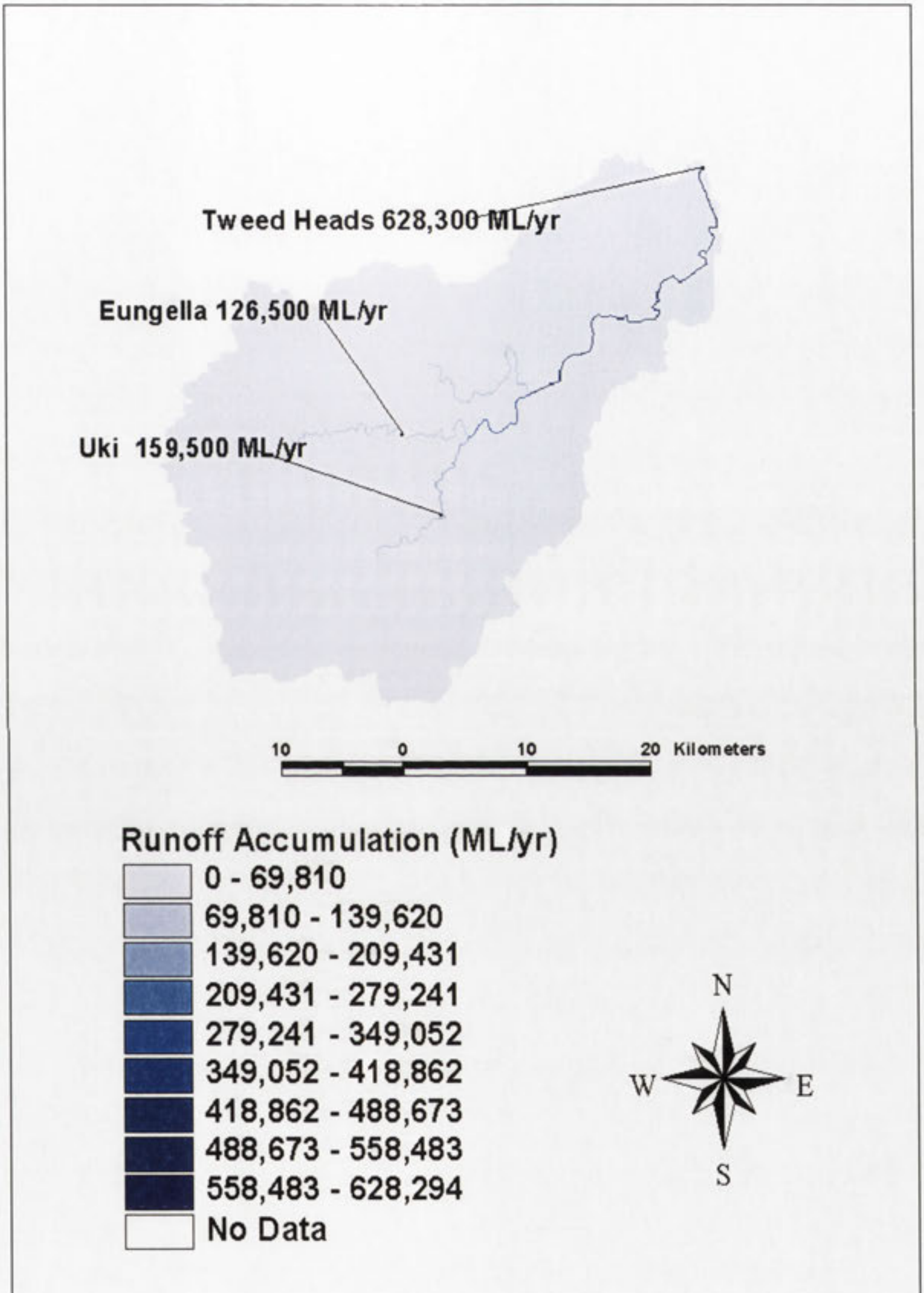


Figure 4.31 Weighted runoff accumulation grid to predict streamflow.

4.2.14 Comparison of Observed Streamflow Versus Predicted StreamFlow

Table 4.5 summaries the observed versus predicted annual streamflow for the Uki, Eungella Sub-catchments and Tweed Catchment. The modelled or predicted annual flows were derived using the weighted runoff flow accumulation grid (Figure 4.31) and a point on the flow accumulation streamline which corresponded to the geo-referenced gauging station.

From the modelling results, the predicted annual flow above Uki is 159, 500 ML/yr, which is slightly higher than the observed flow of 155,189 ML/yr, based on streamflow data obtained from DLWC (1998). RACAC (1995) calculated the average observed streamflow from records dated 1956 to 1995. Based on their calculations, the average annual discharge above Uki is 158,287 ML/yr. This value is around 1,200 ML/yr less than the predicted value obtained from the modelling prediction. Using a runoff coefficient of 0.32 the modelled total mean annual flow for the Tweed Catchment is 628,300 ML (Figure 4.31). The annual flow for the Tweed has been estimated at around 520,000 ML/yr (RACAAC, 1995) with some estimates as low as 418,000 ML/yr (Lin *et al.*, 1995).

Table 4.5 Mean annual streamflow (Observed vs Modelled)

Catchment	Observed (ML/yr)	Predicted (Modelled) (ML/yr)
Uki	**155,189 ***	**159,500**
	158,287 #	
Eungella	**125,381 ***	**126,500**
Tweed	**520,000 #**	**628,300**
	418,000 ^	

* DLWC (1998) Stream Discharge Data

\# RACAC (1995) (using Discharge Data 1956-1995)

^ Lin *et al.,* 1995

A comparison of the runoff depth (Flow/Area ratio Q/A) for the Uki and Eungella Sub-catchment and the Tweed Catchment was also carried out (Table 4.6). The Q/A ratios for the Uki and Eungella were very similar, indicating that both catchments display similar surface flow characteristics. There is a good correlation between the observed and modelled streamflow for both sub-catchments. Interestingly, there is a notable difference in the Q/A ratio between the observed and modelled streamflow for the Tweed. This difference may be attributed to an error in the estimated streamflow rather than an error in the modelling. Using RACA (1995) estimated streamflow of 520,000 ML/yr, we obtain a Q/A ratio 503, which is much lower than the Q/A ratio obtained for the Uki and Eungella. The Q/A ratio for the Tweed, as determined from the modelling results, is 608. This is around 20 mm higher than the Q/A ratio for both the Uki and Eungella Sub-catchments for observed and modelled flows.

Table 4.6 Summary of Annual Flows (ML) for each catchment.

Catchment	Area (A) Km^2	Modelled Flow Q (ML)	Modelled Q/A Ratio (mm)	Observed or Estimated /Flow Q (ML)	Observed Q/A Ratio (mm)
Tweed	1032	628,300	610	520,000 #	503
Uki	274	159, 500	580	155,189	570
Eungella	218	126,500	580	125,381	580

Based on estimates made by RACA (1995).

A comparison was also made between the observed and modelled monthly streamflow data for the Uki and Eungella Sub-catchments. The monthly runoff coefficients for the period 1967 to 1998 were used to derive the monthly runoff and weighted flow accumulation grids from the monthly spatial rainfall grids for the same time period. The modelled flows were determined from the monthly weighted flow accumulation grids and compared against the observed mean monthly flows for the period 1967 to 1998.

There is a good correlation (R^2 = 0.97) (R^2 =0.98) between the modelled and observed mean monthly flows for both the Uki and Eungella Sub-catchments (Figures 4.32 and 4.33). The results indicate that the model is fairly reliable for predicting monthly and annual streamflow in un-gauged catchments, assuming that the physical parameters such as catchment size and topography, do not change significantly and that there is sufficient rainfall data available.

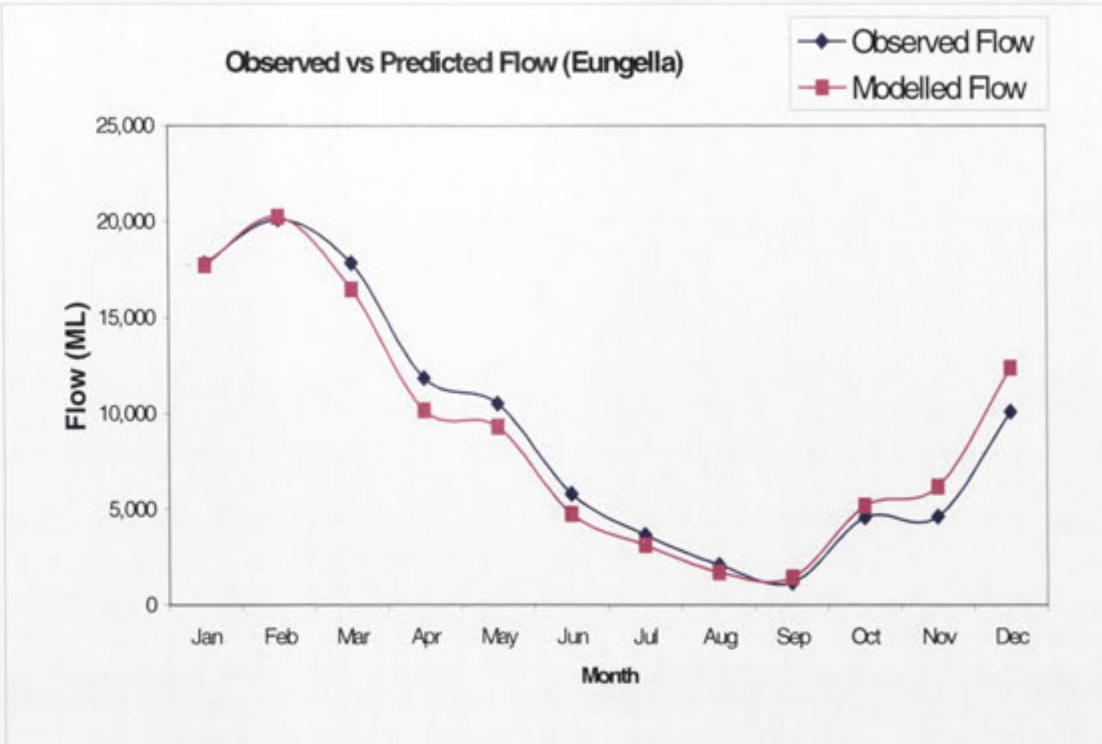


Figure 4.32 Observed flow versus Modelled Flow for the Eungella Sub-catchment ($R=0.98, R^2=0.97$)

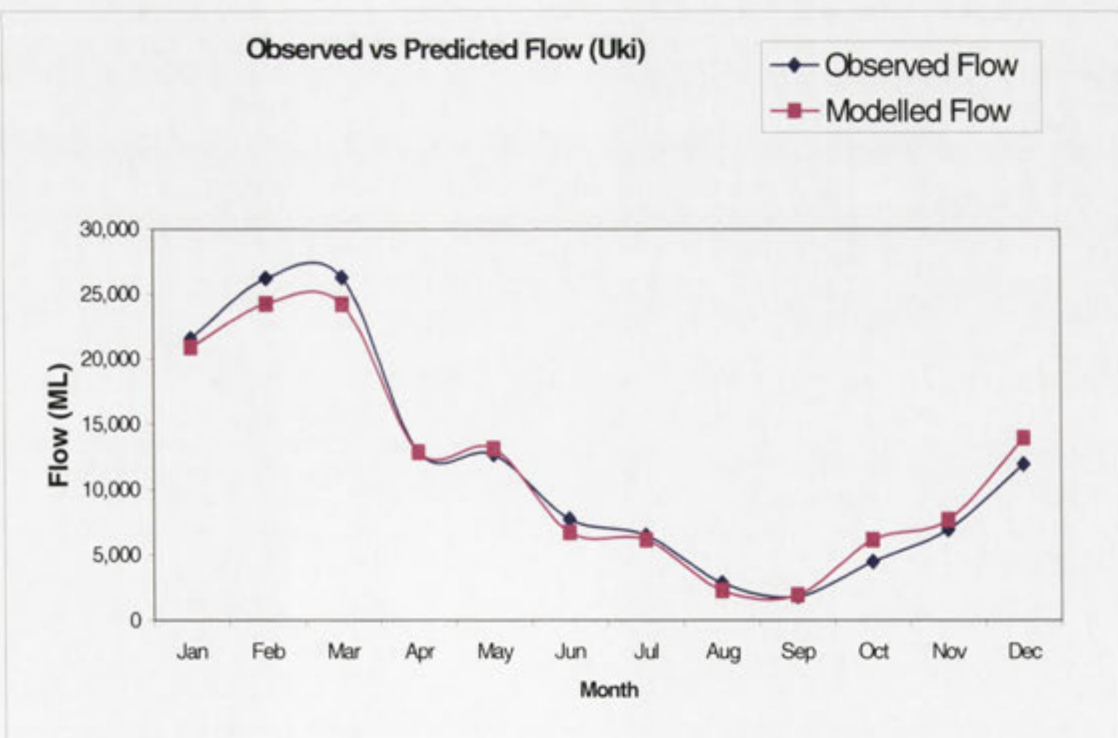


Figure 4.33 Observed flow versus Modelled Flow for the Uki Sub-catchment ($R=0.99, R^2=0.98$)

4.2.15 Determination of Sulfuric Acid Production Loads

First-order estimates have shown that pure sulfuric acid production rates in the Tweed River are 100-200 kg H_2SO_4 /ha/yr (Wilson, 1995) and around 300 kg H_2SO_4 /ha/yr for Richmond swamp land (Sammut *et al.*,1996). In the Cudgen, it has been estimated that leaching rates may be in the order of 0.5 tonne of sulfuric acid per hectare per year (Tweed Shire Council, 1998). Wilson *et al.* 1999, reported that sulfuric acid discharge to surface waters in the Tweed can be as high as 0.3 tonne in one month depending on the climatic conditions. He also estimated that around 2,600 tonnes of sulfuric acid is discharged to the Tweed River during a wet season (Wilson, 1995). However, the total acidity could be much higher if other acidic species are included. The export of acid from acid sulfate soil floodplains to aquatic ecosystems is dependent on the presence of acid in the soil and groundwater, its rate of production, as well as the rate of acid soil water discharge (White *et al.*, 1993).

The oxidation of pyrite on these ASS floodplains appears to have taken place over many years, long before the construction of agricultural drains. The oxidation of these soils is strongly influenced by the dynamics of the watertable and the properties of the soil (Wilson, 1995; Wilson *et al.*,1999; White *et al.*, 1997). Since the top soils contains a large store of acidity, the production of sulfuric acid to a first approximation, can be regarded as constant over long periods (Yang *et al.*,1999). With this assumption, there is a simple linear relationship between the outputs of sulfuric acid and discharge volume.

4.2.15.1 Determination of Sulfuric Acid Land Loads

An annual mean sulfuric acid discharge was assigned to each of the three environmental risk categories, namely, high, moderate and low and presented as a new polygon theme (Figure 4.34). For regions classed as high risk, a value of 0.5 tonnes/ha/yr was assigned. Similarly for the moderate and low a risk category a value of 0.2 and 0.05 tonne/ha/yr was assigned respectively. It would be difficult to accurately map the true spatial distribution of sulfuric acid land loadings across the whole catchment using current soil and water survey techniques. Soil surveys complement the risk mapping data in that they define areas that contain previously oxidised pyritic sediments and their depth from the soil surface.

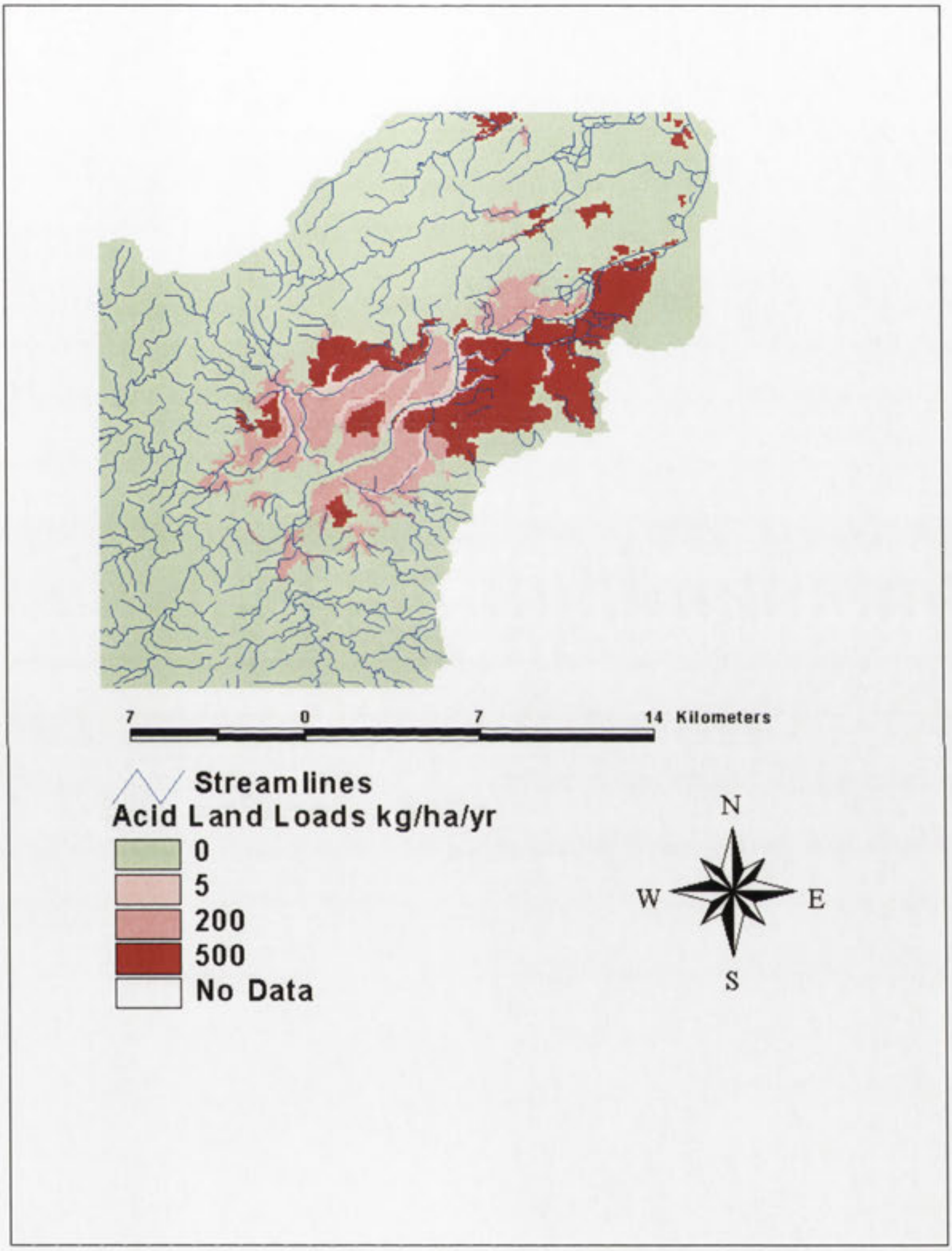


Figure 4.34 Sulfuric Acid Land Loads (Kg/Ha/Yr)*.

(* Grid size is 100 metres square = 1 hectare)

Unfortunately, the risk mapping data alone does not make any distinction between presence of Potential Acid Sulfate Soils (PASS) or actual acid sulfate soils (AASS). We note here that other acidic species such as Al^{3+} and Fe^{2+} are discharged from acid sulfate soil floodplains (Sammut *et al.*, 1996). Here we base our estimates on exports of H_2SO_4 and recognise that this could underestimate total acidic outputs.

4.2.15.2 Estimating the Annual Sulfuric Acid Surface Water Loads

To determine the annual sulfuric acid surface water loads across the Tweed Catchment, a second weighted flow accumulation was carried out on the acid land loads grid shown in Figure 4.34. The ARC/INFO console was used to calculate the weighted flow accumulation using the grid command line function:

Grid: Acidaccumulation = flowaccumulation (flow direction grid, acid concentration grid)

The accumulated annual acid loads in tonnes/yr are shown in Figure 4.35. The total annual quantity of sulfuric acid entering the Tweed River at McLeods Creek is around 2,100 tonnes per year. The total accumulated sulfuric acid load at the point where the Tweed River meets the ocean is around 2,800 tonnes per year.

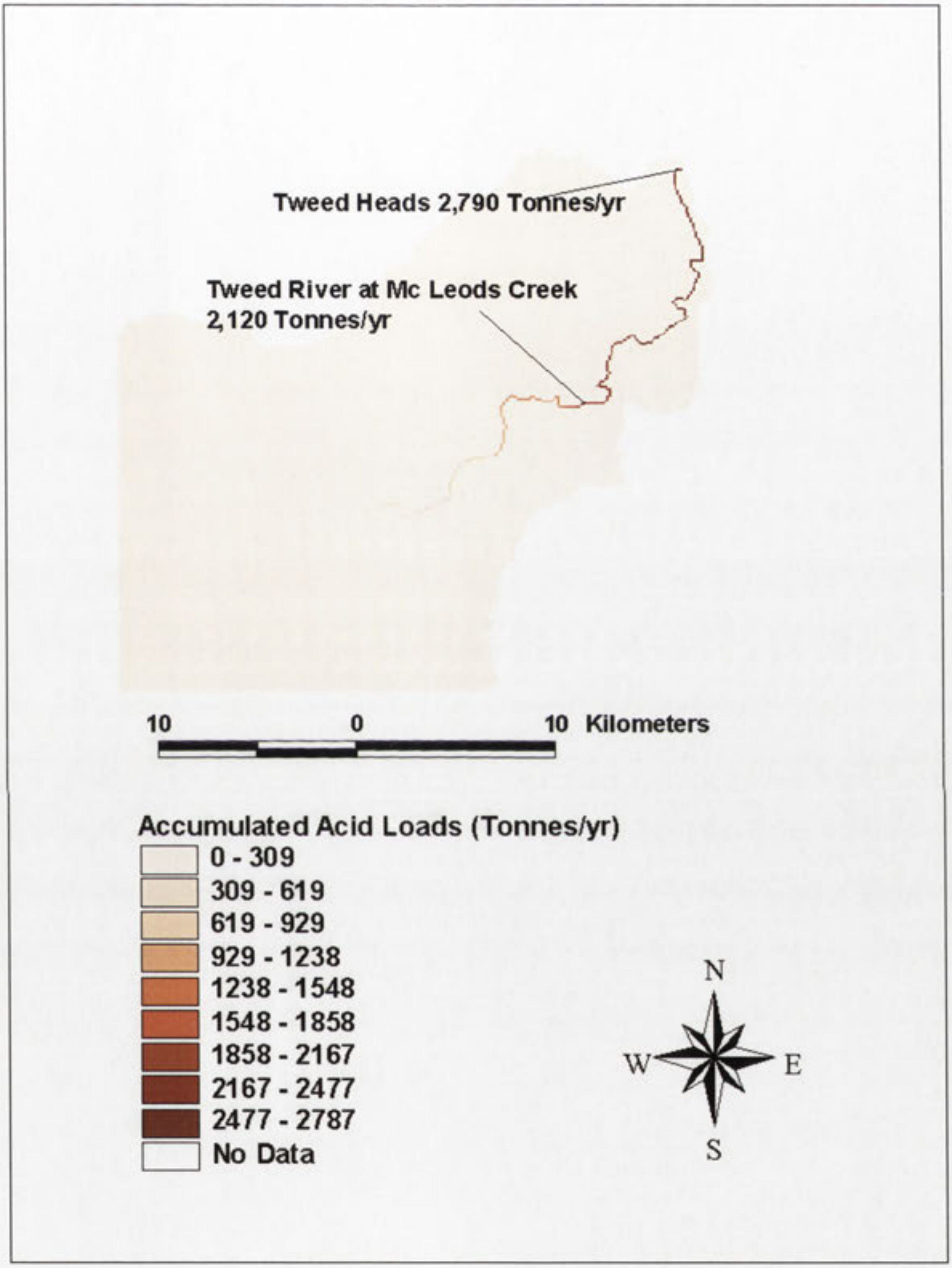


Figure 4.35 Weighted Acid Land Load Accumulation Grid showing acid loads in the Tweed river in tonnes/yr.

4.2.16 Development of a Concentration Grid

In order to determine the non-point acidic pollutant loads in the catchment, it was necessary to first determine the concentration of sulfuric acid in the local runoff. The sulfuric acid production polygon devised in the previous section was first converted to a grid by using the "polygon to grid conversion function" in ArcView. The conversion the polygon to a grid allows a grid by grid calculation to be performed. The concentration of acid in the surface water runoff was calculated by dividing the runoff grid (developed in section 4.2.8) by the sulfuric acid land loads grid (Figure 4.34) using the map calculator function in Arc/View.

The acid concentration in mg/L in the local runoff is shown in Figure 4.36. Concentrations range from 10.4 mg/L to 93.7 mg/L.

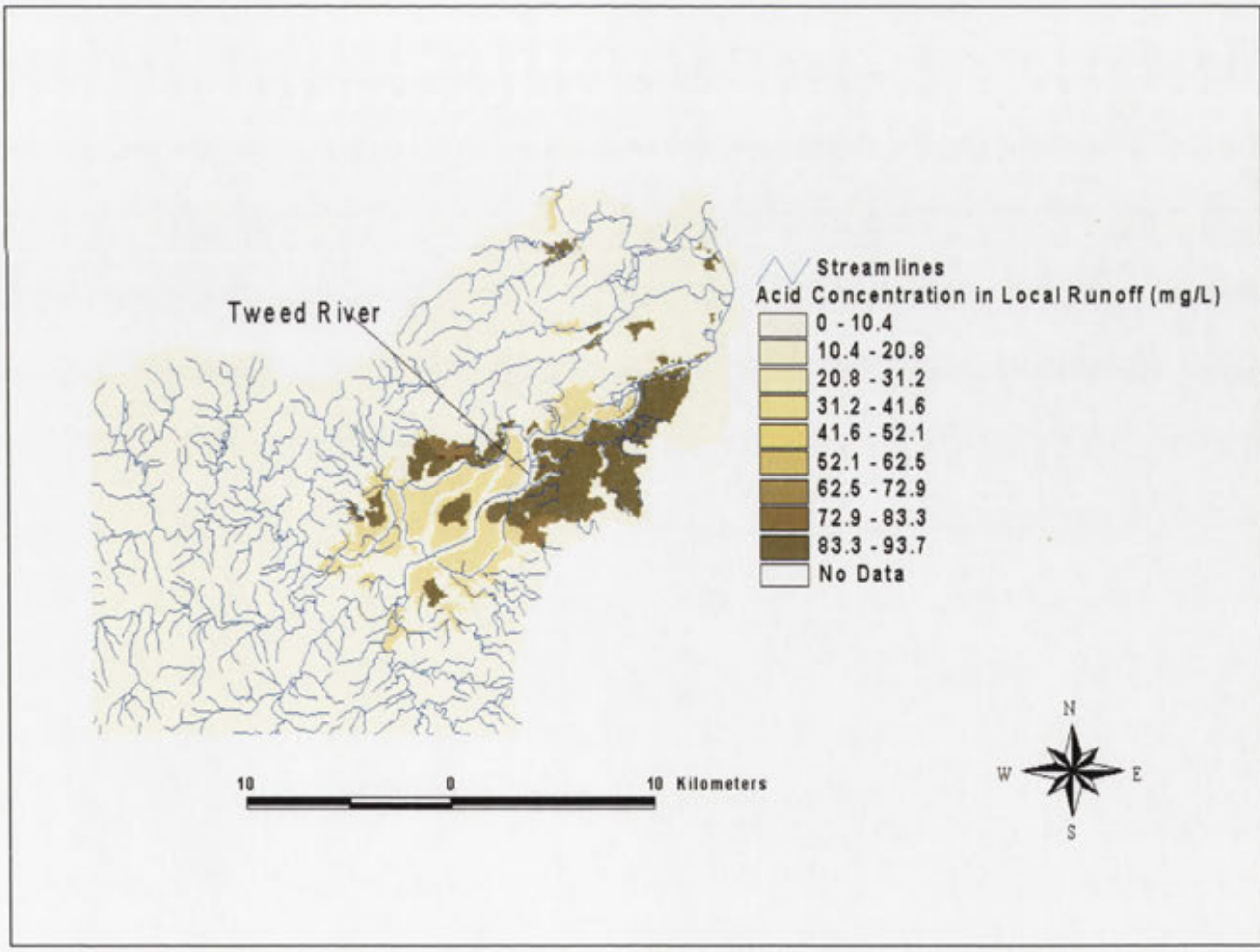


Figure 4.36 Concentration of sulfuric acid grid (mg/L) in local runoff.

4.2.17 Determination of Acid Concentration in Surface Water Runoff

As well as calculating the total sulfuric acid loads and total surface water flow accumulation, an estimated annual concentration of acid in mg/L in the accumulated runoff was also calculated by dividing the acid accumulation loads grid by the runoff accumulation grid, using the map calculator functions in ArcView. Figure 4.37 shows the modelled acid in the accumulated runoff water as a concentration in mg/L.

The concentration of acid varied from 10 to 97 mg/L with the acid confined mainly to the Tweed floodplain. These modelling results provide some insight into the hydrological characteristics of acid sulfate soil floodplains prior to the introduction of flood mitigation schemes. Under these circumstances there would have been considerable inundation of water throughout most of these floodplains areas. Prior to European settlement, coastal floodplains became natural backswamps that remained inundated with water for up to half the year (White *et al.*, 1999a). These backswamps were a valuable water supply for grazing cattle during periods of drought.

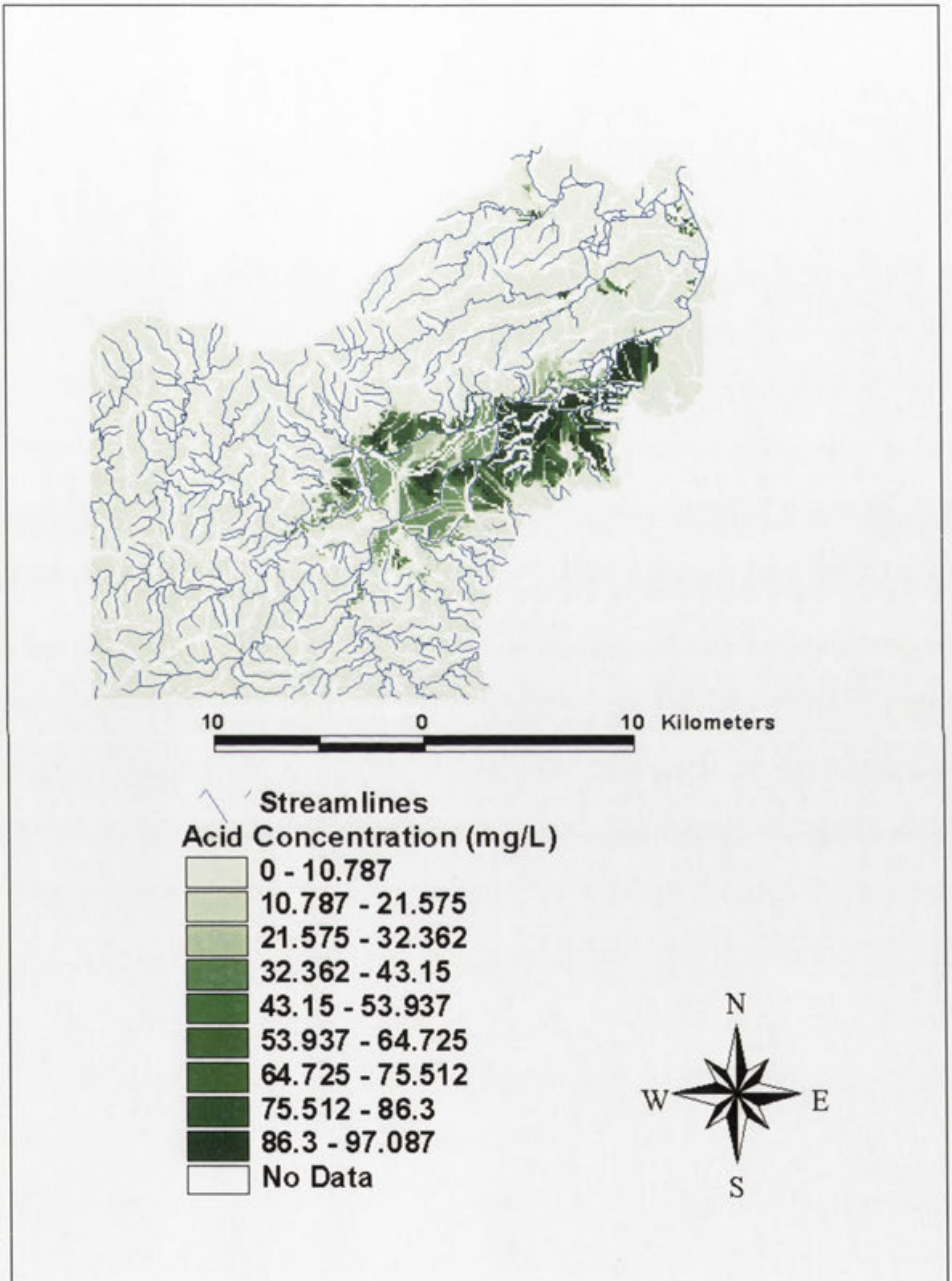


Figure 4.37 Acid concentration in mg/L for the Tweed Catchment.

4.2.18 Incorporation of a Drainage Network

Drainage networks in the Tweed are human-made channels that transport water and its constituents from one location to another, usually from low-lying flood-prone areas to major drains, tributaries and rivers. They are an important factor in determining floodplain hydrology and must be included in modelling hydrological processes in coastal floodplains.

In New South Wales, governments have encouraged the use of coastal floodplains for agricultural cropping which had resulted in the draining of backswamps and floodplain protection through flood mitigation works. For successful cropping of coastal lowlands, drains were designed to remove floodwaters within a five-day period, dramatically altering the hydrology of coastal floodplains (White *et al.*, 1999a).

Major drain construction commenced on the Northern NSW coastal floodplains in the late 1880's and intensified during the 20th century. Some limited drain construction work also occurred during the 1870's after extensive flooding (Stone *et al.*, 1998). The advent of heavy earth-moving equipment during and beyond the 1950's resulted in the expansion and in some cases the deepening of existing drains for flood mitigation purposes (Smith, 1999b; Lin *et al.*, 1995). Flood mitigation works have been conducted on two very different scales, namely the floodplain scale and the local scale. At the floodplain scale, systems were put into place to rapidly divert upland flows and were built by state and local governments. At the local scale, smaller drains have also been constructed on floodplains by Drainage Unions. Drainage Unions were set up under the Drainage Act of 1903 as a cooperative of local farming groups, financed by rates derived from land holders. Financial assistance to Drainage Unions has, however, been affected in recent times resulting in the function being taken over by local councils. It was not uncommon for land holders to construct their own drains that fed into Drainage Union drains.

The impact of agricultural drainage on the surface and groundwater flows of coastal floodplains, is poorly understood (White *et al.,* 1997). However, the impact of these drains on acid sulfate soils in relation to water quality is well documented and understood (Wilson *et al.,*1999; Smith *et al.*,1999; White *et al.,* 1997). Despite the importance of agricultural drains on the water quality, there was little information on the distribution of drainage networks for the east coast of New South Wales. However, a complete description of drain locations, and their size and distribution has been mapped recently by DLWC for NSW acid sulfate soil landscapes (Atkinson *et al.*, 2000). These maps provide details on the location and dimensions of drainage networks where acid sulfate soils occur on a scale of 1:25 000. The maps are designed to be used in conjunction with the acid sulfate soil risk maps (Naylor *et al.*, 1998) and include 1:25 000 topographical maps showing cadastral features and information on river networks and streams. Drain control structures, such as floodgates, weirs, culverts and other structures that might impact on tidal flow, are also included in the database.

The use of drainage data in association with hydrological modelling, provides a unique opportunity to predict a range of environmental scenarios in order to help land managers develop management strategies. Very little modelling has been conducted on the impacts of agricultural drains on acid discharge. To date, the only current detailed hydrological drainage modelling carried out has been confined to the McLeods Creek region of the Tweed Valley floodplain (Yang *et al.,* 1999). Figure 4.38 shows the network of drains in the McLeods Creek region of the Tweed Catchment. The extensive network of drains separate the cane blocks into rectangular blocks. The source data for the individual cane blocks were provided by the Condong Sugar Mill. Extensive drain water quality monitoring of the McLeods creek region has taken place over the last seven years.

Drainage mapping was based on the mapping methodology of Aaso (1996). Here DLWC's 1:25 000 drain mapping data was used to determine the impact of drains on floodplain hydrology and acid discharge. A detailed description of drainage flow direction paths was necessary for modelling water flow and acid discharge. Using ARC/INFO, a flow direction was assigned to each individual drain, similar to the directional streamline input data discussed in section 4.2.12. The ANUDEM program was used to create a new D8 flow direction grid using the drainage directional flow data. By using the weighted flow accumulation function discussed in section 4.2.13, this new D8 flow direction grid was used to model the impacts of agricultural drains on surface water flow and acid discharge in the later chapters of this thesis. This type of analysis has been referred to in this thesis as 'agricultural drainage enforcement'.

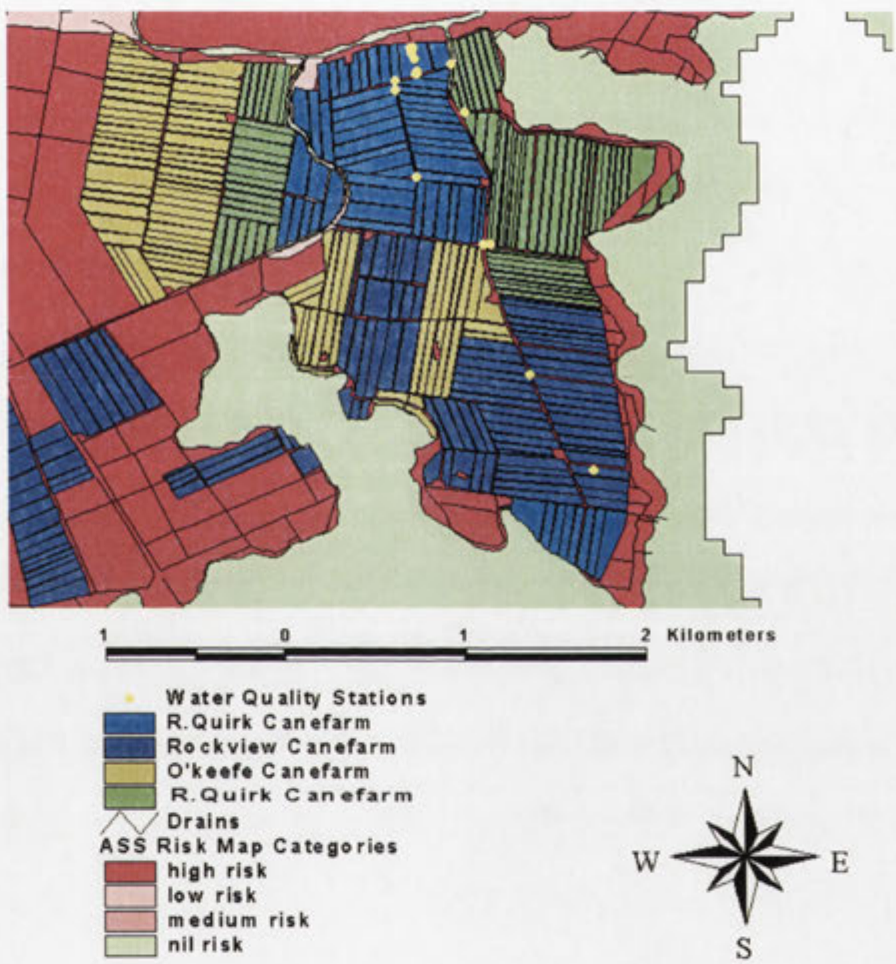


Figure 4.38 Drainage system in the McLeods Creek Catchment of the Tweed. (The source data for the individual cane blocks were obtained from the Condong Sugar Mill).

4.3 Discussion and Summary

The hydrological-water quality model developed here is a lumped parameter model that uses several data sets including elevation, stream network, environmental risk map data, rainfall, streamflow, and drainage map data. The model was developed using a number of programs including ANUDEM, ANUCLIM, ANUSPLIN, Arc/Info and ArcView. The model is displayed in a Geographic Information System (GIS) for visualisation and was developed for the purpose of assessing the impact of climate and land use changes on the export of acid from ASS landscapes. The modelling results presented in this chapter provide a good approximation of the annual and monthly surface water flows for the Uki and Eungella Sub-catchments. There was a good correlation between the modelled and observed monthly mean flows for both sub-catchments (R^2=0.97, R^2 =0.98). In addition, total annual acid loads determined by the model are similar to the acid loads estimated by various researchers. The accumulated sulfuric acid water load to the Tweed River was estimated to be more than 2,000 tonnes per year.

The hydrological water quality model does, however, rely on a number of assumptions. The first assumption relates to the degree of accuracy associated with the acid sulfate soil risk map data and classification process used in the preparation of the risk maps. The information provided by the risk map data is based on the depth to the acid sulfate soil layer below the ground surface and the associated environmental risk resulting from disturbance. Unfortunately, the risk map data does not make any distinction between PASS and AASS. Clearly, for this particular hydrological water quality model, field surveys are an integral part of the modelling process in that they can identify the extent of oxidation across the landscape and the total amount of stored acidity in the soil profile. Therefore, the acid land loads used in the modelling analysis are only an estimate of the total annual acidity released from the soil profile, based on previous interpretations and predictions. A more accurate determination will depend on the development of improved field methodology for the identification and extent of pyrite oxidation, across different acid sulfate soil landscapes (Wilson, 1995). Finally, the model only measures sulfuric acid discharge and does not take into account other acidic species such as iron or aluminium.

The model suggests that if the rate of acid evolution is constant over long periods, the dynamics of the system are controlled by the amount of water entering the system as runoff and leaving the system as evaporation. This is consistent with previous field interpretations which suggest that, apart from the intensity of a rainfall event, the watertable dynamics and the available soil water storage capacity, has a significant impact on water quality (Wilson *et al.,*1999). Therefore, two important characteristics of rainfall, namely the ratio of runoff to precipitation and its variability with respect to time and spatial characteristics, influence the export of acid and other materials into streams. As the rainfall surface maps demonstrate, topography and elevation can influence rainfall intensity and distribution across the catchment. Analysis of the spatial rainfall data, also revealed that there was a noticeable seasonal variation in the spatial distribution in rainfall between the ocean-land fringe and the upper catchment.

The monthly spatial rainfall results presented in this chapter show that there is a difference between long and short-term spatial rainfall data, which supports White *et al's*.,(1997), hypothesis that coastal catchments do not always "operate on average" with respect to climate. The LAPGRD results presented in section 4.2.6 revealed significant differences in rainfall for certain months between the two time periods. When compared with the long-term (1921-1995) data, the analysis of the short-term data revealed that the months February, March, June, July, August and September were drier and May, October and December were wetter. The variations displayed between short and long-term rainfall and the impact of climate and seasonality changes on acidification required further investigation. Chapter 6 examines the trends in rainfall variability in the Tweed while Chapter 7 looks at the climatic effects on acidification and its impacts on the aquatic ecosystem.

In summary, the model developed here is flexible enough to allow for alterations to the input data such as, for example, changes to the runoff coefficient and land loads. The model offers land management groups a tool for assessing the impact of drainage and climate on the transportation of acid and acid products. Remediation options can be put into place to lessen the degree of acid runoff based on model predictions. The hydrological model outlined in this chapter will assist farmers and other stakeholders prioritise their management options. Finally, it is important to note that, when making predictions about streamflow based on rainfall and runoff modelling, it is necessary to ensure that streamflow results are used in conjunction with spatial data for similar time periods.

CHAPTER 5
The Cudgen Catchment: A Baseline Study

(*Photo by Phil Johnston*)

Chapter 5. The Cudgen Catchment: A Baseline Study

5.1 Introduction

The Cudgen Catchment* is a sub-catchment of the Tweed Catchment representing approximately one tenth of the entire Tweed Catchment and is approximately 80 km^2 in size (see Figure 4.4, Chapter 4). Cudgen Lake is around 160 ha in size with an overall depth of 2 metres. The lake is under restricted tidal influence and is connected to the ocean via Cudgen Creek which drains northwards to the ocean via an interbarrier depression located at Kingscliff (figure 5.1). The floodplain region of the catchment consists of Clothiers and Reserve Creeks which drain from the west into Cudgen Lake. This region has been extensively cleared for grazing, resort development, sugar cane plantations and tea tree plantations. Extensive tourism development has taken place around and on the foreshores of the lake. All these activities have led to continued acid drainage into the Cudgen Lake, resulting in the deterioration of water quality and the unprecedented colonization of extensive areas of the lake by the acid-tolerant sedge *Schoenoplectus litoralis* (WBM Oceanics Australia, 1997).

Cudgen Lake was once a renowned prawn nursery and fishing region of the Tweed Valley. Extensive fish and prawn kills occurred during 1991, following a period of heavy rainfall (Easton, 1992). The last major fish kill occurred on the 18 August 1998 which resulted in the death of approximately 45,000 fish. Monitoring of Cudgen Lake and the adjoining floodplains commenced after the 1991 kills. Due to continuing acidification problems, the Cudgen Catchment has recently been identified as an Acid Sulfate Soils (ASS) Management Priority Area in New South Wales (ASSMAC, 1999b).

The relationship between water quality and climate, for the Cudgen Catchment was examined using water chemistry and rainfall records. The GIS hydrology water quality model was also used to estimate the annual sulfuric acid surface water concentrations based on the predicted streamflow. Since the Cudgen Catchment has no observed streamflow data, the predicted streamflow data were derived using the

* For simplicity, the Cudgen Sub-catchment will be referred to as the Cudgen Catchment.

runoff coefficients obtained for the neighbouring Uki and Eungella Sub-catchments in Chapter 4.

Figure 5.1 Aerial view of the interbarrier depression connecting Cudgen Lake to the ocean via Cudgen Creek. Kingscliff on the right hand side of the picture (Photo courtesy of NSW Department of Land and Water Conservation).

5.2 History of Land and Lake Use

The Cudgen Catchment has a long history of different land uses. The floodplain of Clothiers and Reserve Creeks was cleared and sugar cane was grown from the beginning of 1869 with a sugar mill operating by the 1880s (Forsite, 1989). Dairy farming was the most common land use activity in the early 1900's (Bonjer, 1991; WBM Oceanics Australia, 1997). Urban development in the catchment began during the 1960's and has mainly been confined to the township of Bogangar. Towards the later part of the 20th century, crop cultivation became more common.

Pasture, sugar cane, tea, banana and tropical fruit plantations are now very common to the west of Cudgen Lake along the Clothiers and Reserve Creeks. Although most of the floodplain was cleared for cropping, there is still a good cover of native vegetation above the floodplain and surrounding hillsides with considerable estuarine vegetation around Cudgen Lake including mangrove, saltmarsh, swamp oak, oak paperbark, rushland, sedgeland and seagrass (WBM Oceanics Australia, 1997).

During the 1960's, extensive sand mining took place between Cudgen Creek and the ocean resulting in considerable loss of coastal vegetation and resulting wind erosion (WBM Oceanics Australia, 1998). Although attempts were made to restore vegetation following the cessation of mining activities, the restoration primarily involved the planting of non-native species such as the Bitou Bush (WBM Oceanics Australia, 1997).

Both Cudgen Lake and Cudgen Creek have significant conservation value. Since 1995 the lake and surrounding area has been declared a nature reserve with significant conservation value (National Parks and Wildlife ACT, 1974). However, serious acidification problems have severely affected water quality and compromised the conservation value of the lake and surrounding reserve. The lake was once a popular recreational area for tourists and locals (Tunks, personal communication, 1999). In recent times the acid tolerant spike-rush (*Eleocharis spp*) and sedge *Schoenoplectus litoralis* have taken over extensive areas of the lake. Aerial photographs have shown that prior to 1961 the Lake had very few reeds. Reed growth became more prolific around 1979 restricting many water activities such as sailing (See Figure 5.2) (WBM Oceanics Australia, 1998).

5.3 Physical Features

From an ASS management perspective, the Cudgen Catchment has a number of important physical features. One of the most important features is the high ratio of acid sulfate soils to catchment area. This catchment has the highest ratio for any coastal catchment in NSW (White *et al.*, 1999a) making it particularly vulnerable to environmental degradation from acidification. Another critical physical feature of the Cudgen Catchment is the extensive network of agricultural drains situated to the west of Cudgen Lake. The drainage density is 70 m of drains per hectare on average across the catchment. The Cudgen floodplain has the highest drainage density of any other coastal catchment in NSW (G Atkinson, DLWC, personal communication, 2001).

Figure 5.2 Aerial Photograph of Cudgen Lake showing extensive reed growth. The township of Bogangar is shown at the top right hand corner of the picture. (Photo courtesy of NSW Department of Land and Water Conservation).

5.3.1 Topography

A GIS incorporating the topographical features of the Tweed River Catchment, including the Cudgen Catchment, was developed by DLWC (1998) using the 1991, 1:25,000 series of colour aerial photographs and from original topographical maps from the NSW Land Information Centre. The topography of Cudgen Catchment ranges from gently undulating to precipitous, with hill slopes greater than 50%. Close to 40% of the catchment is classified as level, with a slope of 2 % or less (i.e Cudgen floodplain). Around 12 % of the catchment has gently undulating hills and around 20% is mountainous country. The slope attributes of the Cudgen Catchment are displayed in Table 5.1 and are also presented in the GIS (Figure 5.3).

Table 5.1 Slope attributes of the Cudgen Catchment.

Hectares	Code	Description	Slope	Percentage of catchment
993	B	Gently Undulating	2-5%	11.60%
485	C	Undulating	5-10%	5.60%
1725	F	Mountainous	33-50%	20%
1336	E	Hilly	20-35%	15.60%
575	D	Rolling	10-20%	6.70%
3415	A	Level (Floodplain)	0-2%	39.9%
20	G	Precipitous	>50%	0.20%

5.3.1.1 Digital Elevation Model of the Cudgen Catchment

The 100 metre DEM of the Cudgen Catchment (Figure 5.4) was delineated from the 100 metre Tweed Catchment DEM produced using the ANUDEM program discussed in Chapter 4. The Cudgen Catchment is of very low elevation with three main ridges to the west of the lake. From the DEM, the highest peak in the catchment is approximately 388 metres in height.

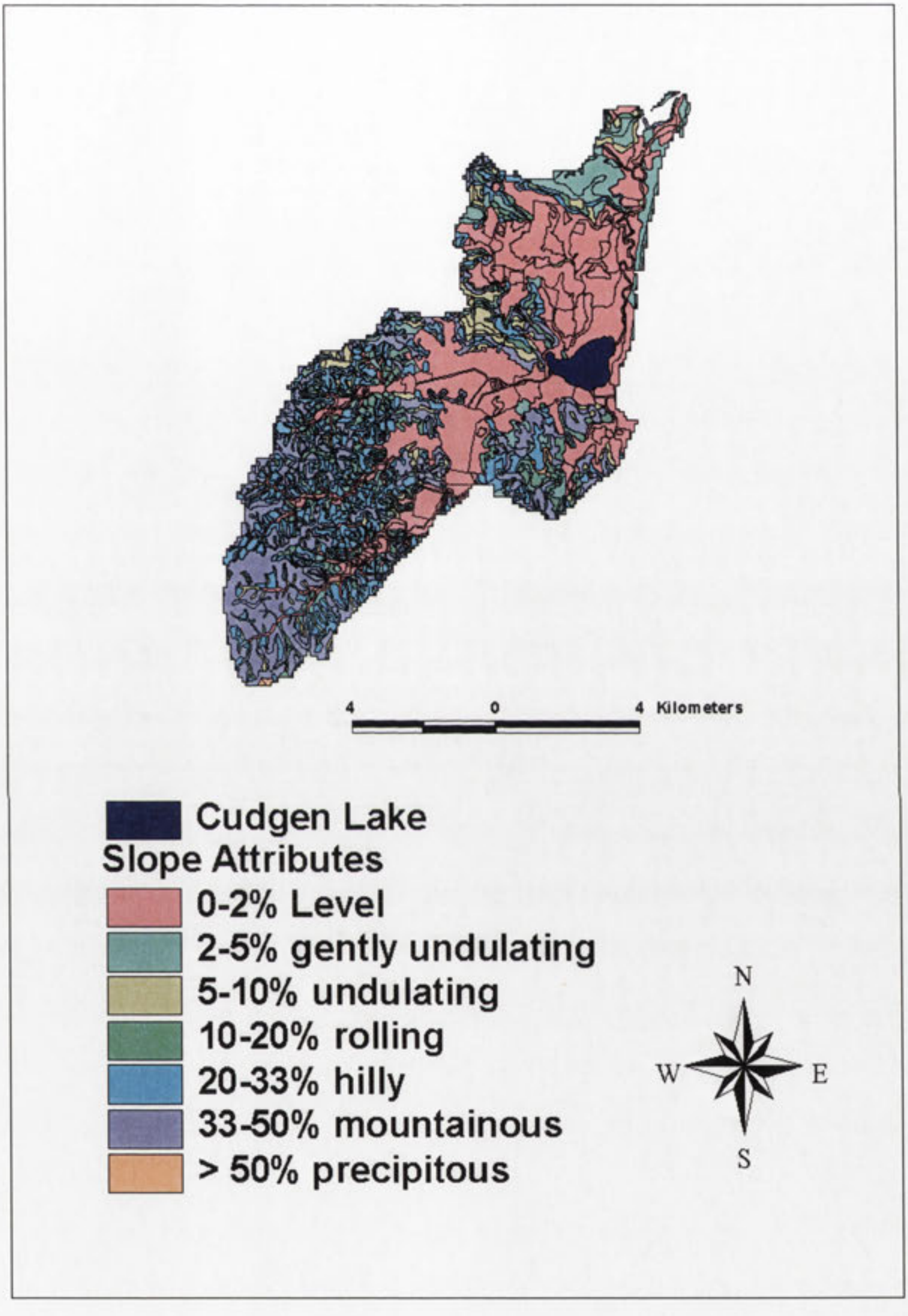


Figure 5.3 Slope attributes for the Cudgen Catchment. The dark brown regions represent the flood plain with a slope between 0-2%.

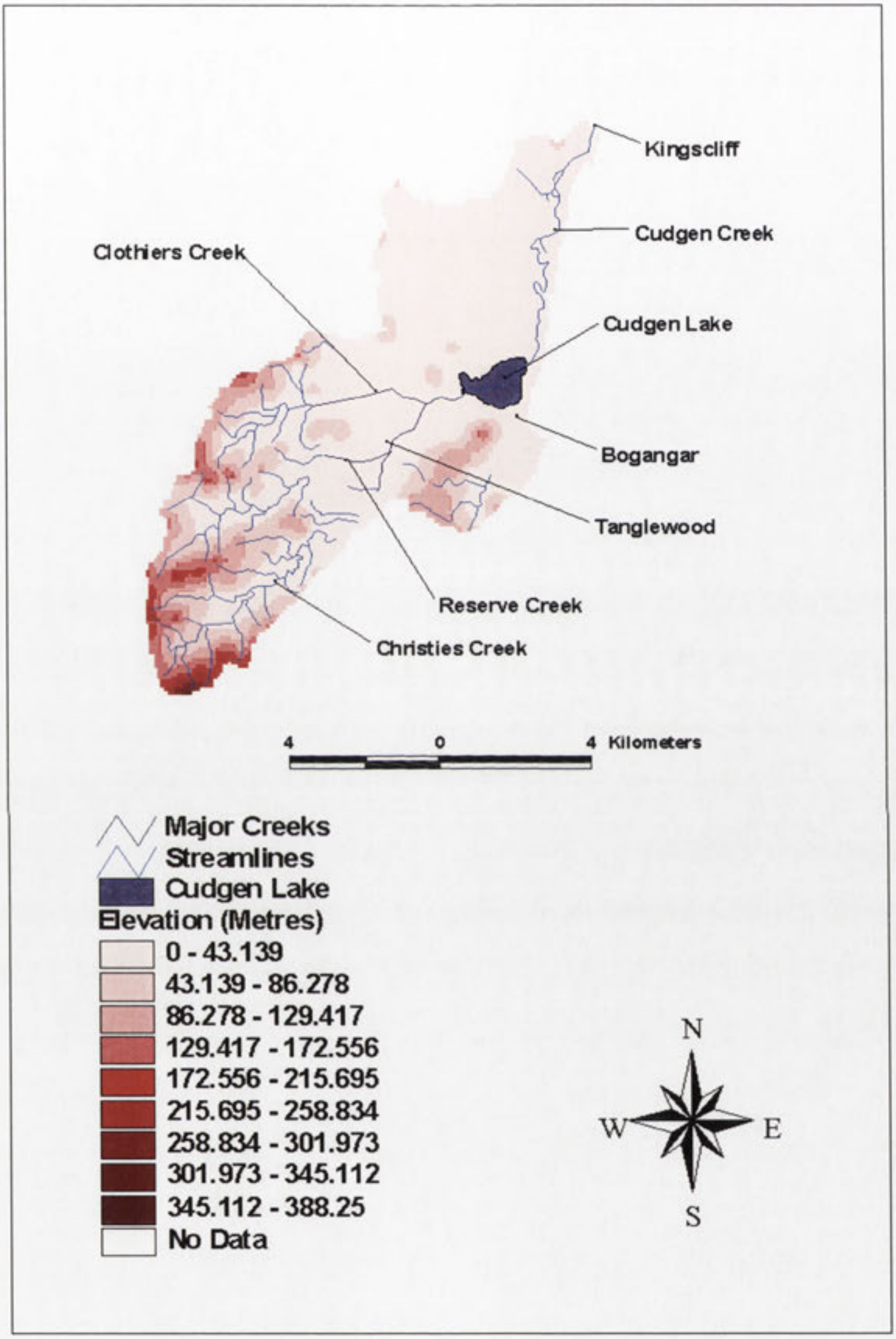


Figure 5.4 Cudgen Catchment delineated from the Tweed 100 metre DEM.

5.3.2 Current Land Use Activities

Land-use attributes for the Cudgen were analysed as part of the Tweed River Catchment Study using 1991 1:25,000 topographical maps provided by the NSW Land Information Centre (Hamilton, 1998). In addition to aerial photographs, other sources were used to construct the vegetation characteristics of the catchment. These included vegetation maps obtained from the Murwillumbah Council and the Caldera Environment Centre. These maps were constructed from ground surveys. State Forests of NSW provided data on old growth forests which were also included in the survey (Hamilton, 1998). Land-use activities generally change over time, however, a rapid visual survey of the catchment during March 2002 revealed that no real change had occurred with respect to the land-use activities and vegetation types displayed in the attribute maps. The only exception to this was sugar cane cropping. Although the attribute mapping suggests that sugar cane cropping was once the dominant crop grown on the Cudgen floodplain, field observations confirm that it is no longer an intensive farming activity in the Cudgen. Sugar cane plantations were removed to make way for the Tanglewood golf course and tourist development during the late 1980s (Tweed Shire Council, 1998). Sugar cane farming is now primarily confined to the southern section of the floodplain and occupies an area of around 170 hectares. (M. Tunks, Tweed Shire Council, personal communication, 2001).

The current agricultural activities are grazing for beef and dairy cattle, bananas on the hill slopes with northerly aspects, sugar cane on the floodplain regions with vegetable production on some parts of the Cudgen floodplain and on the basalt caps (Hamilton, 1998). Some wood products are harvested, mostly on private property, with some new plantations noted in the Tanglewood area during 2002. The recent field survey also noted that a majority of the Cudgen floodplain was mostly pasture with very little grazing by beef and dairy cattle. This land appeared unproductive, due primarily to the extensive acid scalding which was clearly evident in some of the lower parts of the catchment. Aerial photography shows vast regions of the Cudgen floodplain affected by acid scalding (Figure 5.5). These areas are unproductive in terms of agricultural use and require urgent management attention (White *et al.*, 1997).

Current land use activities are shown in Figure 5.6 and in Table 5.2. Forest makes-up a large portion of land cover, occupying around 38 percent of the catchment. This is followed by natural or improved grassland which covers 35 percent of the catchment. Horticulture and cropping cover a combined area of around 21 percent of the catchment. The horticultural activities include orchard farming (stone fruit), banana, macadamias, mangoes and tea plantations as well as vegetable and flower farming. The largest activity form this group is orchard farming (493 hectares) followed by vegetable and flower farming (386 hectares). Most of these activities are confined to the northern region of the catchment near the township of Cudgen. Tea plantations make-up around 18 percent of the horticultural activities in the catchment area.

Forested regions are mainly confined to the higher elevations to the south of the catchment and around Cudgen Lake. These regions mostly contain native forest which have remained relatively undisturbed. Forest covers the largest area of the catchment (around 38%) followed by grass land (35%). There is around 344 hectares of natural wetland plant species and around 161 hectares of natural swamp land. Urban and tourism development, including the Tanglewood development has been limited representing around 1 percent of total catchment land use.

The importance of vegetation cover and how it relates to surface and groundwater dynamics is discussed in Chapter 8.

Figure 5.5 Aerial view of the Lower Cudgen Catchment floodplain showing some acid scaling (red tinge).

Table 5.2 Land use coverage as a percentage of the total Cudgen Catchment.

Land Cover	Percentage Land Use
Pasture and Sugar Cane Cropping	8
Horticulture	13
Grassland	35
Forest	38
Water	4.2
Mining	1.8
Urban	1
Utility	<1

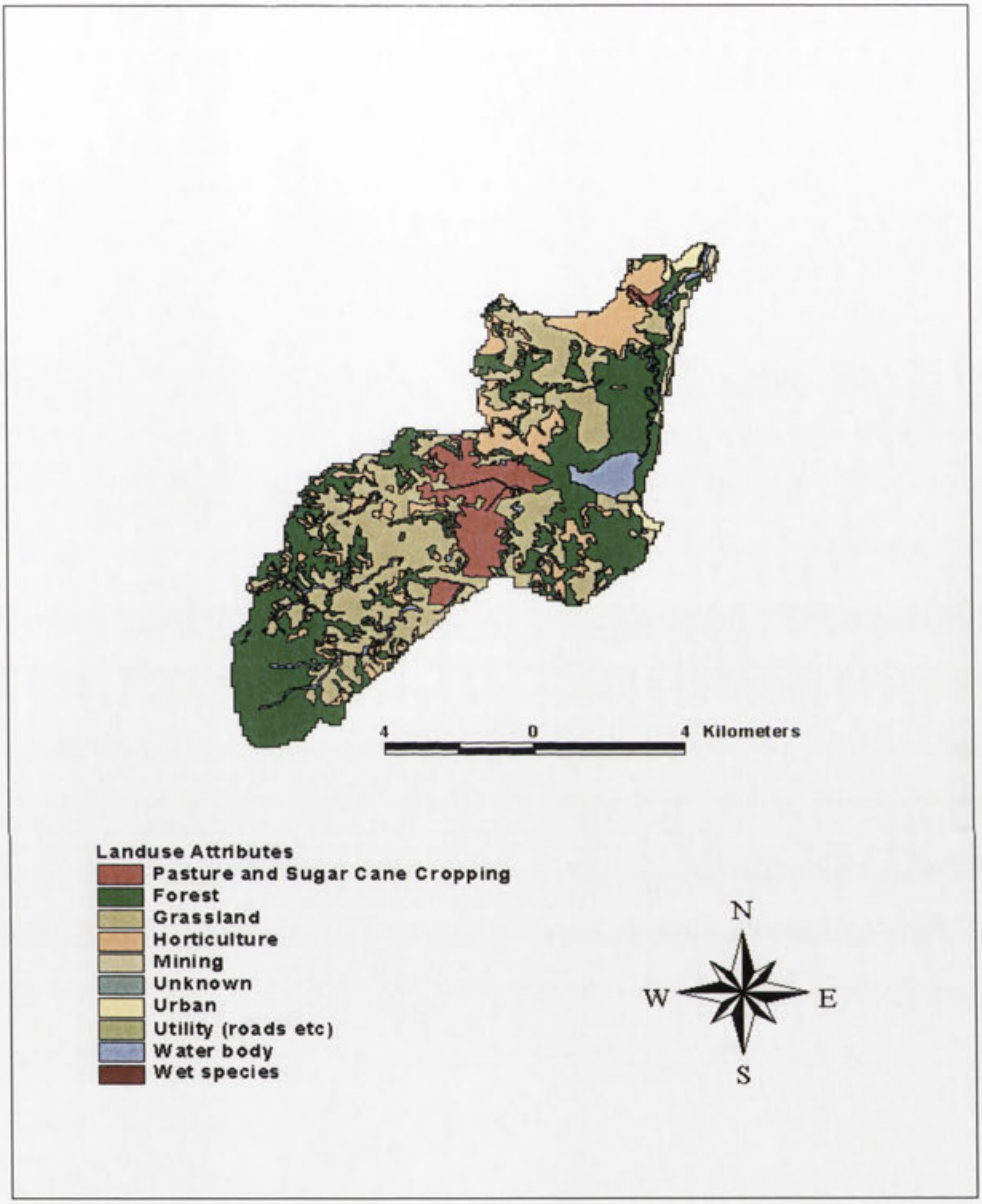


Figure 5.6 Land-use attributes for the Cudgen Catchment.

5.3.3 Soils and Geomorphology

The Cudgen Catchment is a part the caldera of the extinct Mt Warning volcano. To the west of Cudgen Lake, the geomorphology is characterised by narrow valleys containing alluvium and minor peat deposits with prominent hills consisting of metamorphosed sedimentary rock (sandstone, mudstone) (WBM Oceanics Australia, 1998). The floodplain of the Cudgen Catchment is classified as a fluvial floodplain resulting from Holocene infilling which occurred about 6500 years ago (Roy and Thom, 1981). The sedimentation that occurred during the marine transgression, around the late Pleistocene and Holocene period, is very typical of many coastal regions of NSW (Roy, 1984a,b; Thom and Chappell, 1975).

5.3.3.1 Soil Types

The soils of the Cudgen Catchment have previously been mapped by Morand (1996) as part of 1:100 000 scale soil landscape mapping series. The soil information contained within the maps was derived mainly from site inspections and from geological information surveys which describe the floodplain soils as brown and black alluvial clays. The soil landscape is dominated by estuarine derived soils (Cobaki soil landscape) in the lower floodplain and alluvial soils (Cudgera soil landscape) around the upper reaches of the floodplain of Clothiers, Reserve and Christies Creeks (Johnston, 1999).

5.3.3.2 Geomorphology and ASS Risk Mapping

Numerous soil surveys, involving detailed chemical analyses have been carried out on the floodplains of Cudgen Catchment (Beer, 1992; Johnston, 1999). Johnston (1999) and Beer (1992) examined the distribution of pyritic sediments in and around Clothier and Reserve Creeks. Soil samples taken from several sites revealed pH values ranging from less than pH 3 to depths of less than half a metre, to pH 4.5 of depths of about one metre (Figure 5.7). There is more actual acidity stored in the soil profile down to a depth of one metre in measurements taken from the upper part of the catchment. Beyond one metre, the pH profile changes rapidly from AASS to PASS. This sudden transition from AASS to PASS is characteristic of acid sulfate soils

(Wilson, 1995). The actual acidity below 1.2 metres is negligible and represents about one tonne per hectare per profile (Johnston, 1999). In the lower catchment, where there is severe acid scalding, the actual acid layer is at the ground surface but the depth of the actual acid sulfate soil layer, is only around 0.3 metres. In the low-lying areas, where there is severe acid scaling, there is the potential for further acidification through the oxidation of sulfides.

Chemical analysis of the soil profile also revealed high concentrations of the acidic cation species aluminium and iron with correspondingly high levels of electrical conductivity. According to Johnston (1999), low acidity profiles were apparent in regions where runoff has eroded topsoil layers or where extensive fluvial sedimentation had once occurred. In some parts of the catchment, it has been estimated that the depth of potential acid sulfate soils is up to 40 metres (White 2001, personal communication).

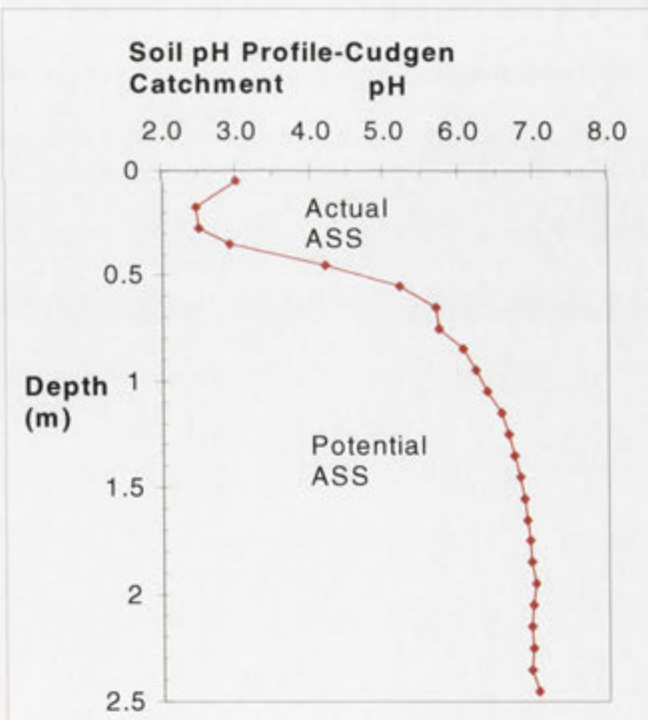


Figure 5.7 Variations in the depth of Acid Sulfate Soil material taken from soil pH profiles across the Cudgen floodplain (modified from Johnston, 1999).

Based on the geomorphology and the acid sulfate soil risk mapping data (Table 5.3 and Figure 5.7) (Naylor *et al.*, 1998), around 520 hectares of the catchment is alluvial floodplain containing acid sulfate soil layers at a depth of less than one metre below the soil surface. Around 509 hectares are classified as estuarine sandplain with acid sulfate soil layers at a depth of one metre or less. These regions are classified as ASS high risk areas in accordance with the map class description categories discussed in section 4.2.9 of Chapter 4. Around 366 hectares are alluvial floodplain containing acid sulfate soil layers at a depth of approximately two metres. This region has been classified as medium or moderate risk. Another 23 hectares of alluvial flood plain contain acid sulfate soil layer, buried four or more metres below the surface. This region has been classified as low risk. There are other geomorphic regions that pose no immediate threat to the environment, even though they contain acid sulfate soil layers at a depth of one to two metres. These include regions of swamp sandplains and channels. These regions are usually covered with water and have very low oxidation potential and are only an environmental problem if disturbed through dredging activities. The total area to the west of the lake contains around 790 hectares of acid sulfate soils.

Other regions, where urban or tourism development has occurred, are classified as 'disturbed terrain'. These regions include sites consisting of sealed roads, car parks, golf courses and buildings. In the Cudgen Catchment, large areas of disturbed terrain were generated in floodplain regions. The most recent of these developments was the discontinuous Tanglewood golf course (Tulau, 1999a). Table 5.3 summarises the geomorphology of the catchment and the depth to acid sulfate soil layers from the soil surface. The results of this table are also displayed in the GIS (Figure 5.8).

Table 5.3 Surface soil geomorphology of the Cudgen Catchment and the associated depth to acid sulfate soil layers from the soil surface.

Geo Code	Hectares	Description	Depth to ASS	ASS Risk Factor
B	6	Beach		
HAn2	19	Alluvial channel	2metres	Moderate
HAp1	521	Alluvial plain	1 metre	High
HAp2	97	Alluvial plain	2 metres	Moderate
HEa1	509	Estuarine sandplain	1metre	High
HEc	55	Estuarine tidal creek		
HEm	153	Estuarine bottom sediments		
HWa2	14	Aeolian sandplain	2metres	Moderate
LAp2	113	Alluvial plain	2metres	Moderate
LAp2(p)	156	Alluvial plain	2metres	Moderate
LAp4	23	Alluvial plain	4 metres	Nil
LSa2(p)	116	Swamp sandplain	2metres	Moderate
LSn1	203	Swamp channel	1metre	High
LWa2	13	Aeolian sand plain	2metres	Moderate
LWa2(p)	756	Aeolian sandplain	2metres	Moderate
LWd2	5	Aeolian dune	2metres	Moderate
LWd2(p)	1	Aeolian dune	2metres	Moderate
NWd4	1	Aeolian dune	4metres	Nil
O	5598	No Classification		
X1	42	Disturbed terrain	1metre	High
X2	69	Disturbed terrain	2metres	Nil
X4	126	Disturbed terrain	4metres	Nil

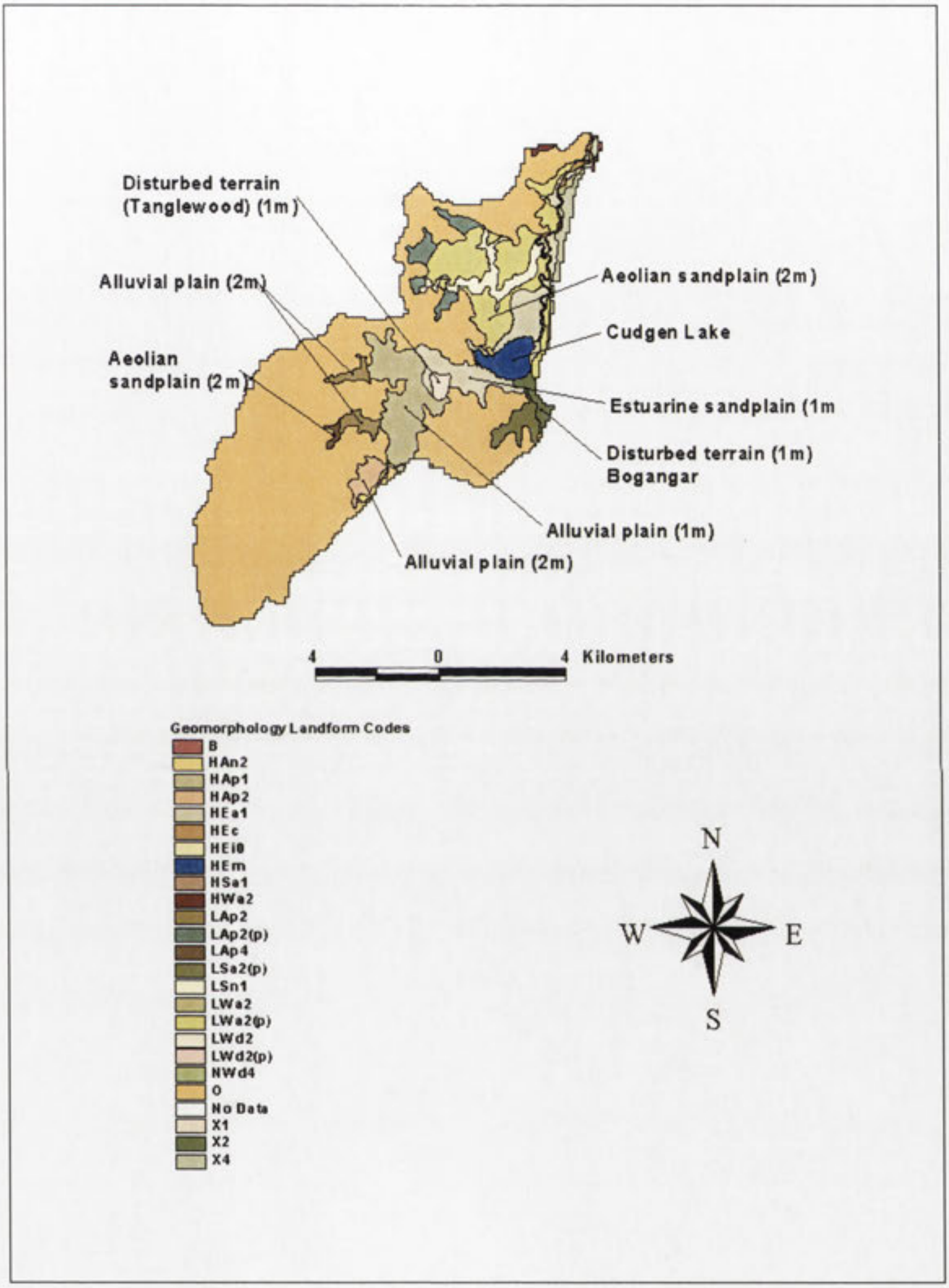


Figure 5.8 Geomorphology Landform Codes used to ascertain the level of environmental risk associated with land use activities. The map description for each code is given in Table 5.3.

5.3.3.3 Acid Land Loads

Estimates of the total amount of sulfuric acid contained within the soil profile have been made based on random soil sampling. Within a 223 hectare area of Cudgen Catchment there is around 30–40 tonnes of stored sulfuric acid per hectare (Johnston, 1999) to a depth of 1 metre. South of Reserve Creek, estimates of the amount of sulfuric acid are between 20-25 tonnes per hectare (Johnston, 1999). These results represent only 70 percent of the total acidity and does not take into account other acid ionic species that contribute to low pH (M. Melville, personal communication, 1999). Therefore, the true amount of stored acidity in the soil profile would most likely be as high as 50 tonnes of total acid per hectare. Other estimates have put the total amount of sulfuric acid at around 50 tonnes of sulfuric acid per hectare, giving leaching rates of around 0.5 tonne from the soil per year (Tweed Shire Council, 1998).

It is difficult to clearly define the spatial distribution of sulfuric acid land loads based on the current soil surveys carried out by Johnston (1999). However, these surveys are beneficial in that they clearly determine the extent of oxidation within the soil profile, which the risk map does not provide. Therefore, based on these surveys and in conjunction with the risk map data, it is possible to make an assessment of the distribution of stored acidity throughout the catchment. Sulfuric acid land loads were assigned a discharge value based on the same methodology as discussed in Chapter 4 section 4.2.15.1 using the geomorphology map data shown in figure 5.8. Acid sulfate soils regarded as high risk, were assigned a discharge value of 500 kg/ha/yr, and for moderate risk, a value of 200 kg/ha/yr.

The geomorphology to the north of Cudgen Lake (Figure 5.8) contain estuarine sand plains (Ea1). Aeolian sand plains (Lwa2(p)) have a high environmental risk because of the strong likelihood that disturbance to these regions will result in oxidation of ASS and the release of acid into the surrounding ecosystem. This region has been classed a high risk area containing potential acid sulfate soils. However, since there has been little or no disturbance to this region, there would be negligible acid export into Cudgen Lake (ASSMAC, 1999b) and therefore no value has been assigned to this risk category. This region also falls within the Cudgen Natural Reserve where major land-use activities such as drain and/or road construction and urban development are prohibited under the National Parks and Wildlife ACT (1974). The low-lying land immediately to the west, south-west and north of Cudgen Lake is zoned as a SEPP14 coastal wetland (Tweed Shire Council, 2001) and cannot be drained. A majority of the surface water flow (80%) and acid discharge originates from the floodplain to the west of Cudgen Lake. The sulfuric acid land loads for Cudgen Catchment are shown in Figure 5.9.

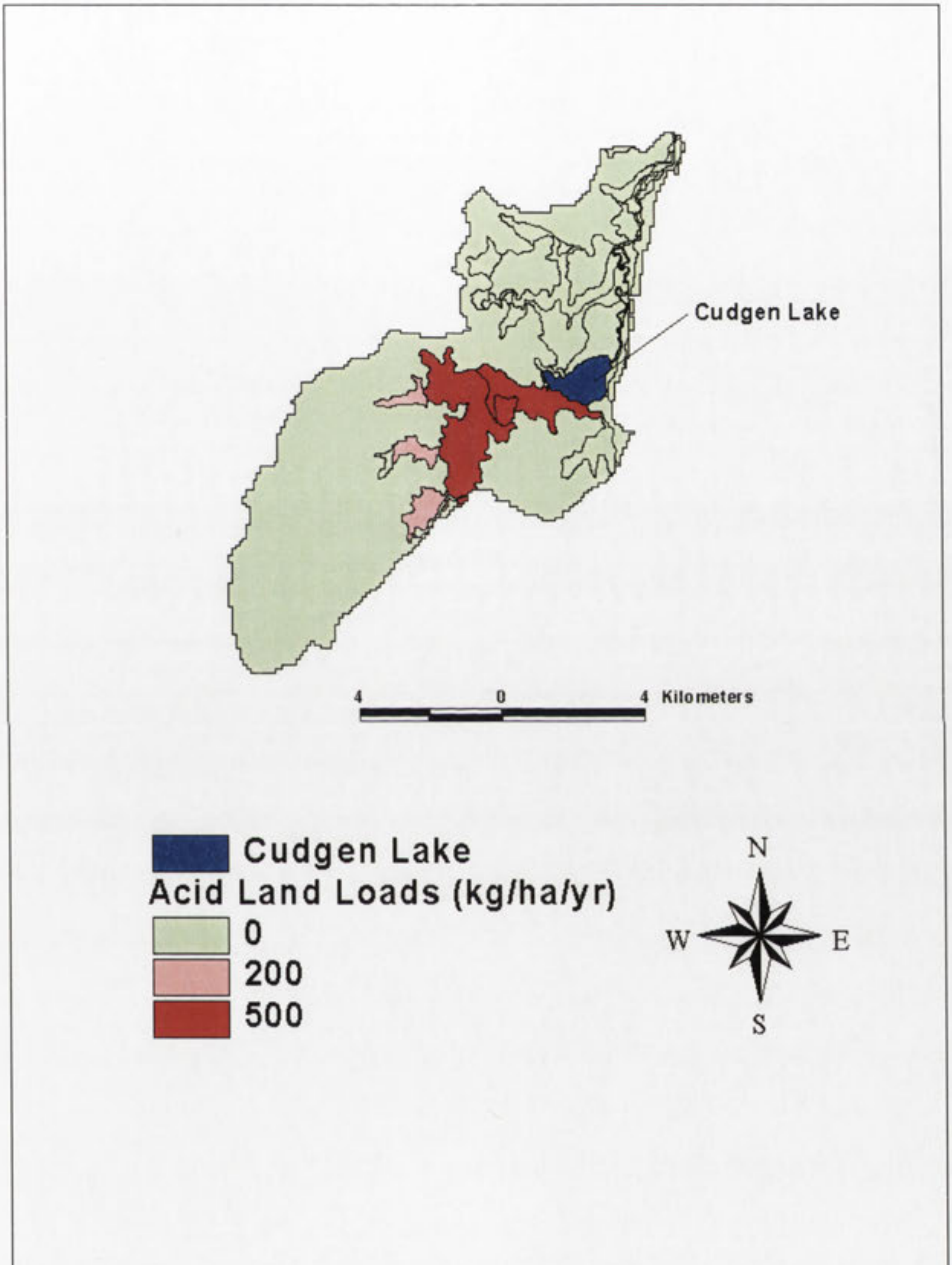


Figure 5.9 Sulfuric Acid land loads kg/ha/yr for Cudgen Catchment.

5.3.4 Drainage and Flood Characteristics

Cudgen Lake and the floodplains upstream of the lake, act as a natural flood retention basin, with floodwaters released to the sea via Cudgen Creek at approximately one-twentieth of the inflow rate (WBM Oceanics Australia, 1998). Roy (1975) had estimated that the flood discharge rate to Cudgen Lake is in the range of 140 to 280 m^3/s. During periods of heavy flooding an area up to 6 times the normal lake area is in flood, with floodwaters inundating the regions immediately to the west and north of the lake (Tulau, 1999a). Flood waters are a major problem in the extremely low-lying regions of the catchment and the construction of agricultural drains was seen as an important issue for landowners. Drainage works began around the 1960's with the existing watercourse of Clothiers and Reserve Creeks re-engineered to include straightening and deepening (Bonjer, 1991; Tulau, 1999a). The impact of these engineering activities on the hydrology of Cudgen Lake has never been assessed. According to the residents of Bogangar and the surrounding foreshore of the lake, flooding had become progressively worse prior to 1973 with floodwaters in and around the lake taking longer to recede. The physical deterioration in the drainage network and increased drainage construction by drainage unions was seen as the causative factor for an increase in floodwaters (WBM Oceanics Australia, 1998). Despite the concerns of local residents, there is no evidence to suggest that drainage construction or other human-induced activity had any significant impact on altering flood levels in the lake (Roy, 1975).

The Clothiers Creek Drainage Union is responsible for managing several major drains in the Clothiers and Reserve Creek area. The design, construction and maintenance of the drainage system has been primarily the Tweed Shire Council's responsibility since the 1960's (Soros-Longworth and McKenzie, 1980). During 1990/91, extensive drainage works (see Figure 5.10) took place as part of the Tanglewood golf course development. The construction of these drains led to acidification problems downstream of the development. No major drainage works have been carried out since this time, except for the re-engineering of drains to accommodate the Chinderah to Yelgun Pacific Highway upgrade (Cramer *et al.*,2002).

In order to model the impact of agricultural drains on acid discharge, drainage map data were obtained from DLWC (Atkinson *et al.*, 2000). Drains were mapped at a scale 1:25 000 showing drain depth, width and spoil. The drainage data described in this section was used to create a new DEM and D8 flow direction grid, containing flow direction paths for each drain. The methodology and construction of the drainage maps were previously described in more detail in section 4.2.18 of Chapter 4. Figure 5.11 shows the mapped distribution of the drainage network in the catchment and the depth range of drains. The width of drains within the catchment is shown in Figure 5.12. Drainage depth varies from a minimum of 0.5 metres to 3 metres with the major drains having a depth of 2 metres. Most of the drains have a depth between 0.5 and 1 metre. Only one drain has a depth of more than 2 metres. The drainage widths vary quite significantly from 1 metre to 36 metres. The major drain network of Clothiers and Reserve Creeks has a drainage width less than 23 metres and a drainage depth between 1 and 2 metres. Some of the major drains have drainage widths between 23 metres and 36 metres (Figures 5.11 and 5.12). The drainage network of the Cudgen Catchment is a combination of natural and artificial drains, with most of the drainage network directing the flow of water into one tributary which then feeds into Cudgen Lake.

Figure 5.10 One of several large drains on the Cudgen Catchment floodplain measuring around 36 metres in width.

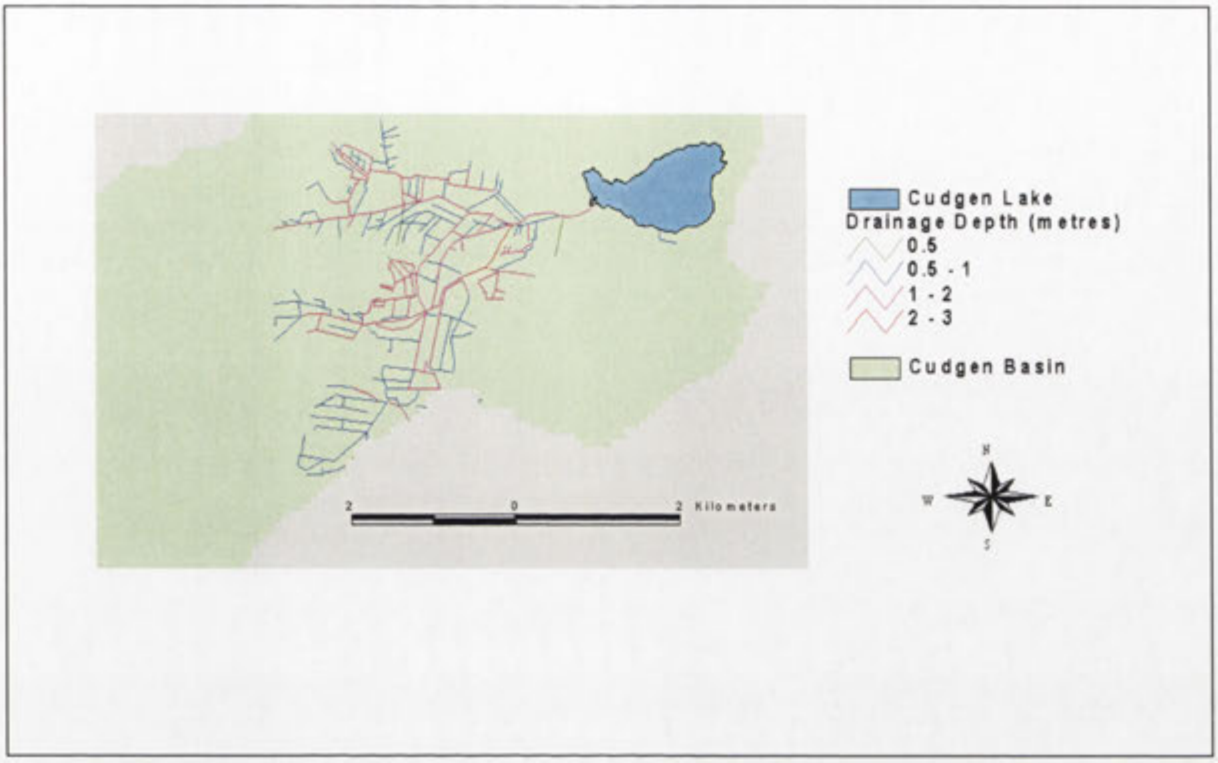


Figure 5.11 Drainage depth in metres for the Cudgen Catchment.

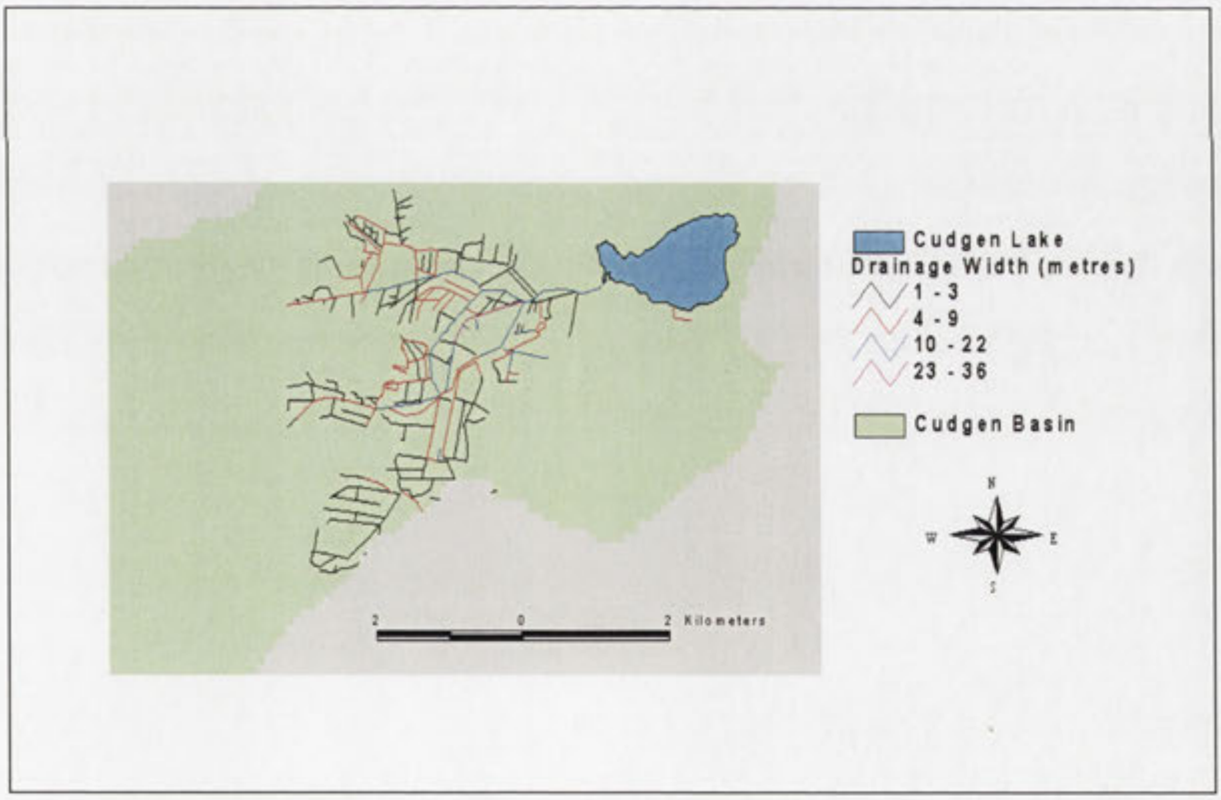


Figure 5.12 Drain width in metres for the Cudgen Catchment.

5.3.5 Tidal Exchange

Cudgen Lake is connected to the ocean via Cudgen Creek. Tidal movements in Cudgen Lake have undergone considerable change since the early 1970's. Cudgen Creek in its natural state has experienced considerable morphological and tidal changes, due in part to the configuration of the creek and its entrance to the ocean. The entrance to the ocean had often become congested or blocked due to sand build up from beach erosion. Consequently, tidal regimes were unpredictable with tidal conditions ranging from significant ocean tide penetration to no tidal influence at all (WBM Oceanics Australia, 1998). To ensure better tidal regimes and regular tidal flushing, the mouth of Cudgen Creek was altered after 1970 to ensure that it remained opened. Also, at the same time, the intertidal areas of Cudgen Creek were filled in and the land reclaimed for development. Sand mining has also contributed to the constriction of the creek. These activities have severely reduced the width and depth of the tidal channel. Consequently, the tidal regime of Cudgen Lake is considered as weakly tidal (WBM Oceanics Australia, 1998). Figure 5.13 shows the variation in tidal regimes for Cudgen Creek under existing conditions. For an ocean tide of mean range 1.0 metres, the mean water level for Cudgen Lake is approximately 0.26 metres above MSL and has a range of 0.03m. The current tidal range is around 0.02-0.05m. Prior to 1970 the tidal range was around 0.1m (WBM Oceanics Australia, 1980). Given the small tidal range in Cudgen Lake, significant fluctuations are evident only during large spring tide cycles.

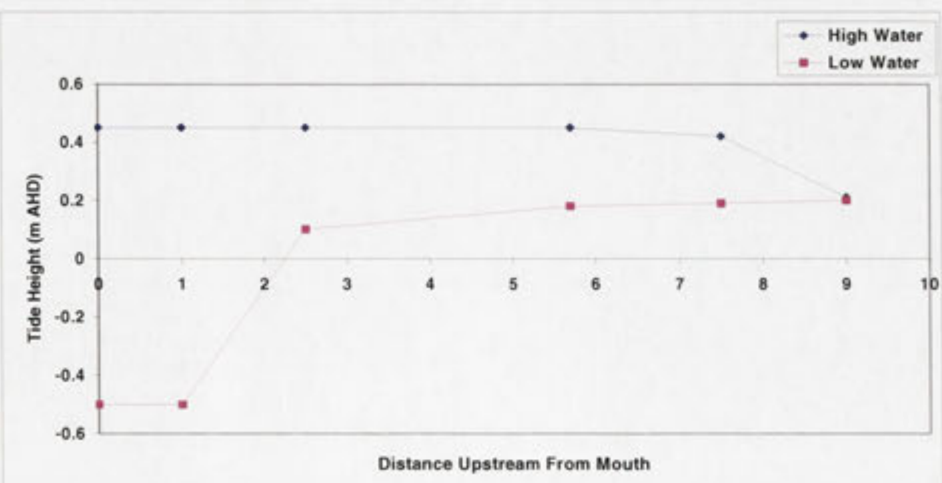


Figure 5.13 Typical variations in tidal levels in Cudgen Creek for an oceanic tidal range of 1.0 (WBM Oceanics Australia, 1998).

5.3.6 Climate

5.3.6.1 Annual and Monthly Rainfall Surfaces

The Cudgen Catchment has a humid, subtropical climate with a wet season from December to March and an average annual rainfall of 1800 mm (Bureau of Meteorology, 1988). Individual rainfall stations, such as Kingscliff, receive as much as 1928 mm in a single year (Forsite, 1989). The summer months are warm to hot and the winters generally warm and dry. Figure 5.14 shows the annual spatially averaged rainfall for the Cudgen Catchment based on long-term rainfall records from 1921- 1995. The distribution of annual rainfall varies across the catchment with 1740 mm of rainfall in low elevation regions, to 2411mm in higher regions west of Cudgen Lake. Interestingly, the amount of annual rainfall across the catchment is fairly uniform with only 671 mm difference between the highest and lowest annual rainfall value. The annual mean spatial rainfall for the Cudgen is 1840 mm. This is 20 mm higher than the annual mean spatial rainfall for the Tweed Catchment, which receives 1820 mm. On average, the coastal catchment of the Cudgen receives slightly more rainfall than the Tweed. The Bureau of Meteorology annual mean rainfall for the Northern NSW coastal region is 1800 mm (Bureau of Meteorology, 2003a).

Monthly spatial rainfall was also examined and rainfall surfaces produced using rainfall data for the period 1921-1995 (Figure 5.15). The amount of rainfall that falls across the catchment is seasonally dependent. Rainfall is low during the winter months (less than 150 mm but greater than 50 mm) with less rainfall in the upper part of the catchment during the months of August and May. Approximately 60% of the rainfall falls from December to April (Figure 5.16) with more significant falls in the upper catchment. The months of February and March are usually the wettest months with falls as high as 353 mm per month. It is not uncommon for flash flooding to occur with above monthly average rainfall occurring within a 24 hour period (State Pollution Control Commission, 1987). From May to August the distribution of rainfall across the catchment becomes more uniform, with the south-eastern coastal region of the catchment receiving slightly more rain than the upper catchment.

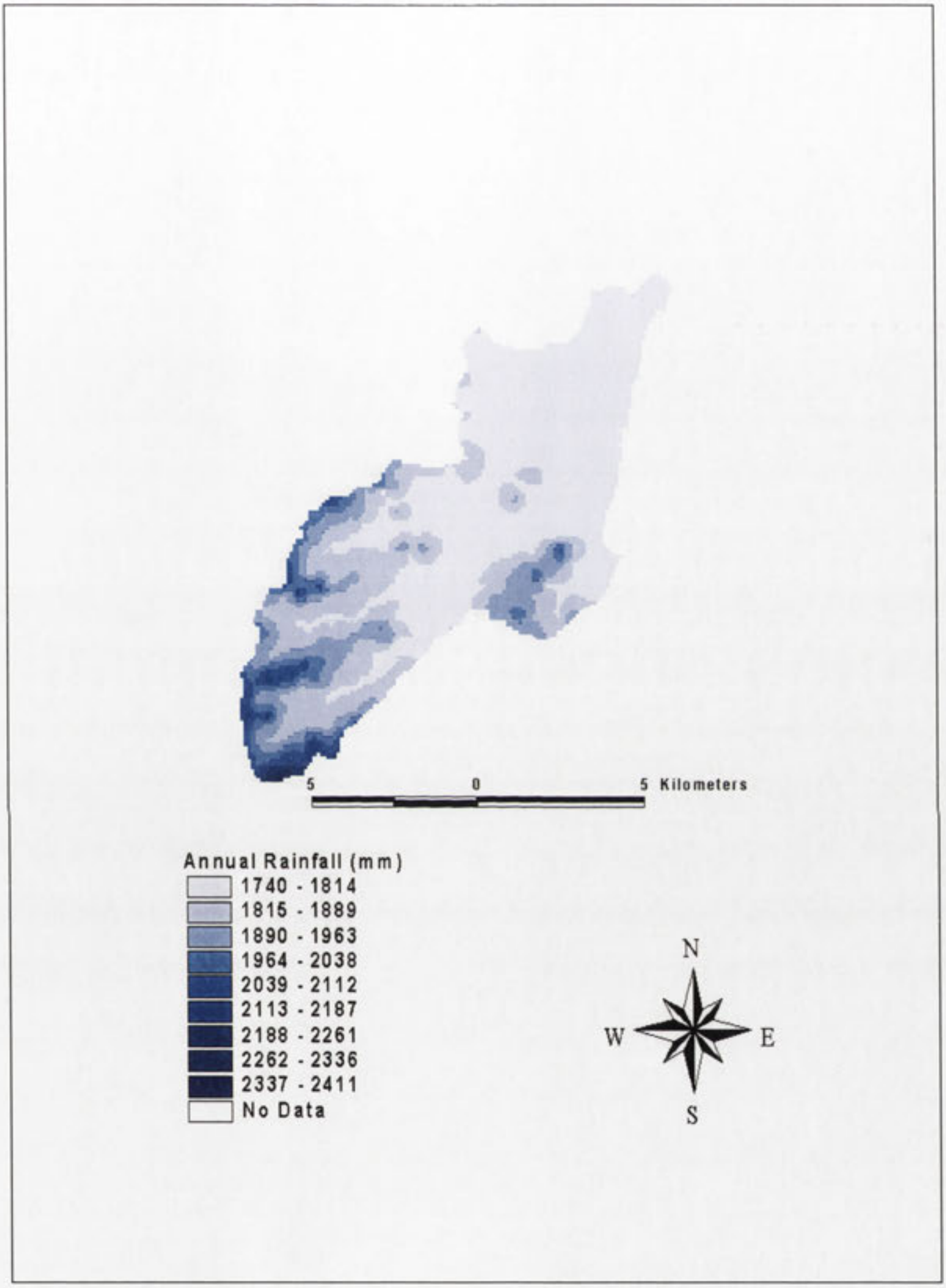
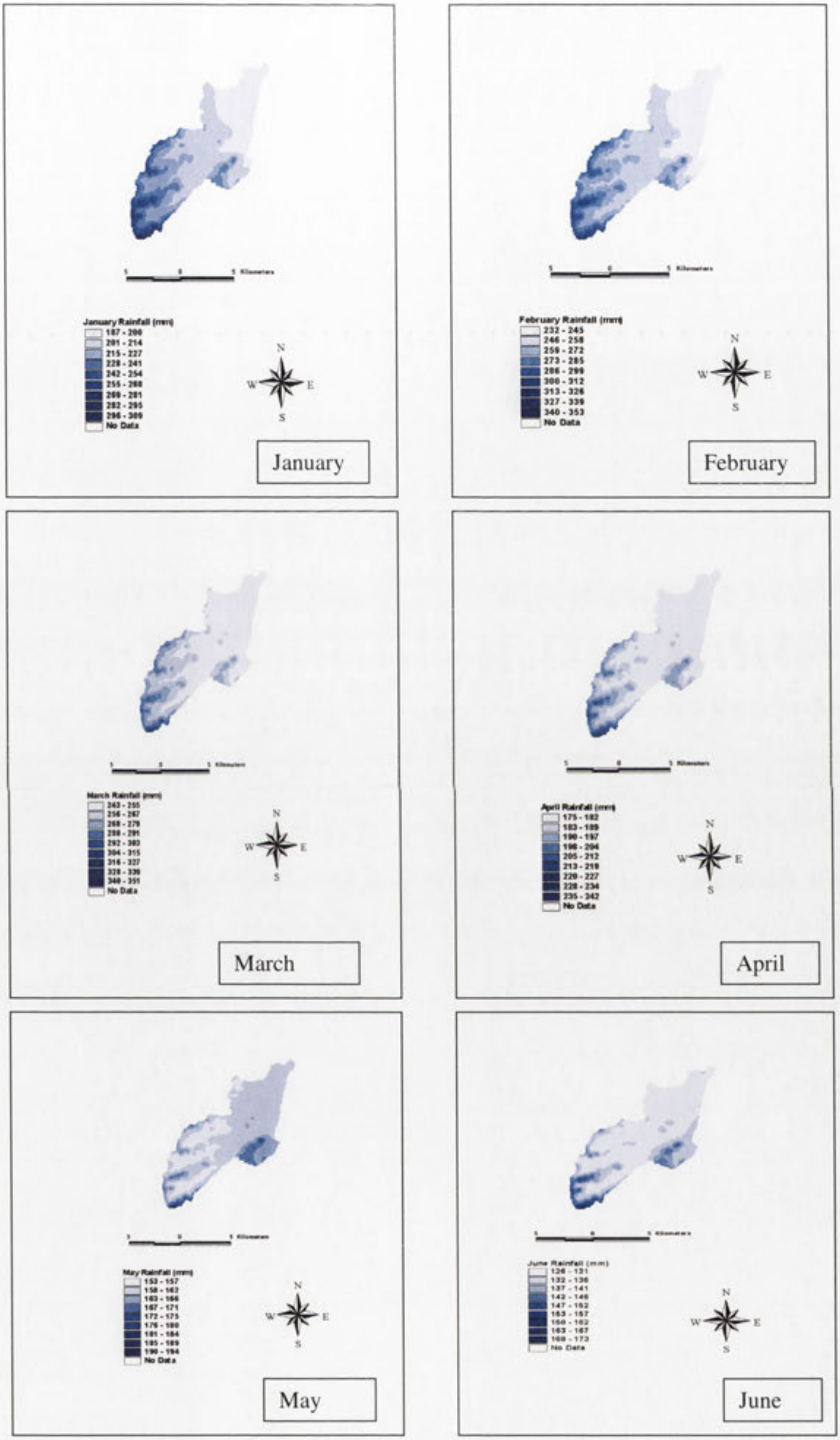
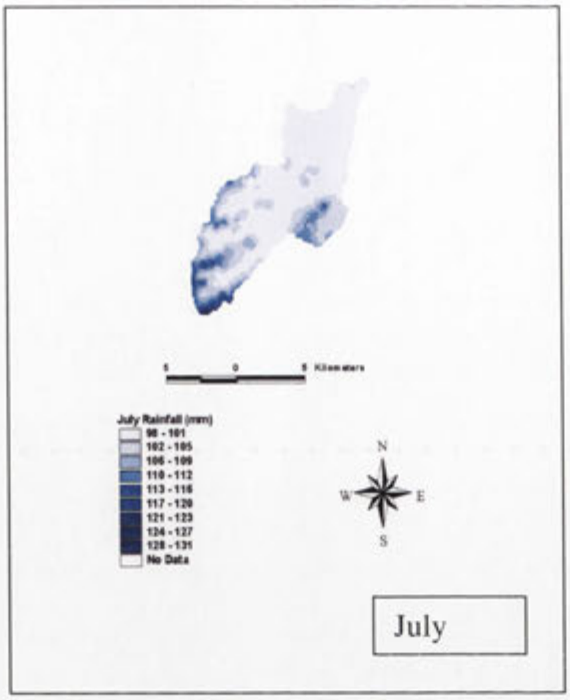
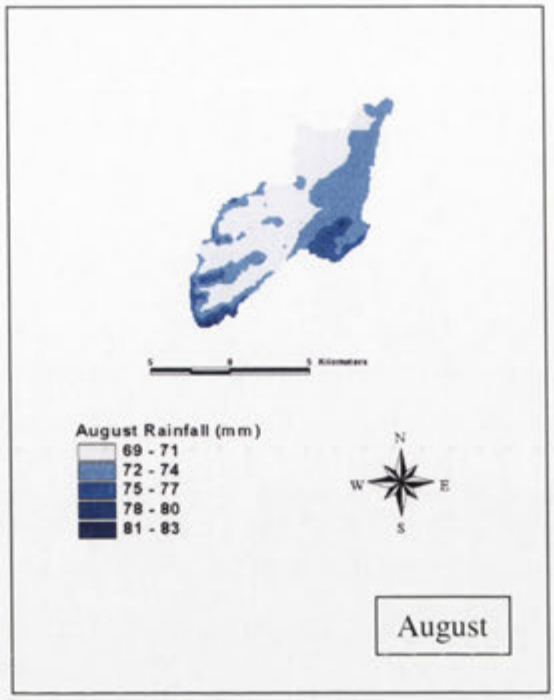


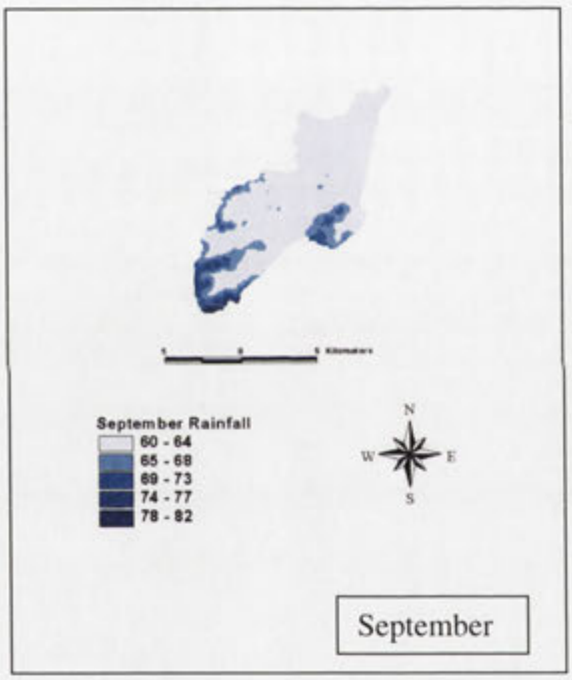
Figure 5.14 Spatially distributed annual mean rainfall for the Cudgen Catchment.

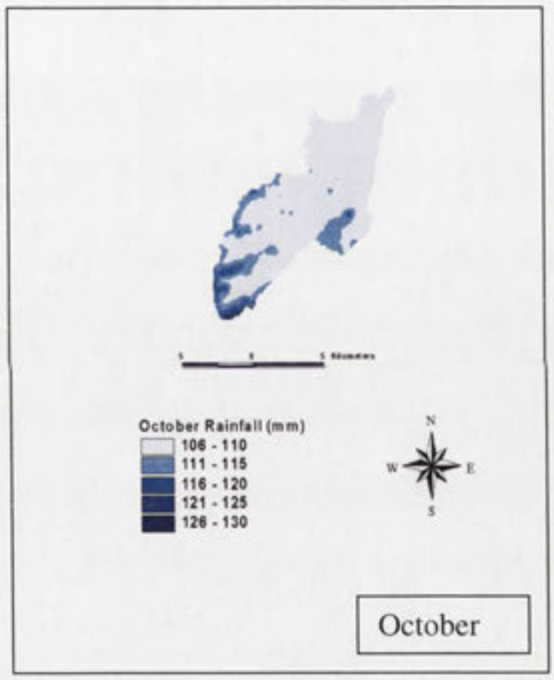
Figure 5.15 Spatial Distribution of monthly mean rainfall for the Cudgen Catchment.

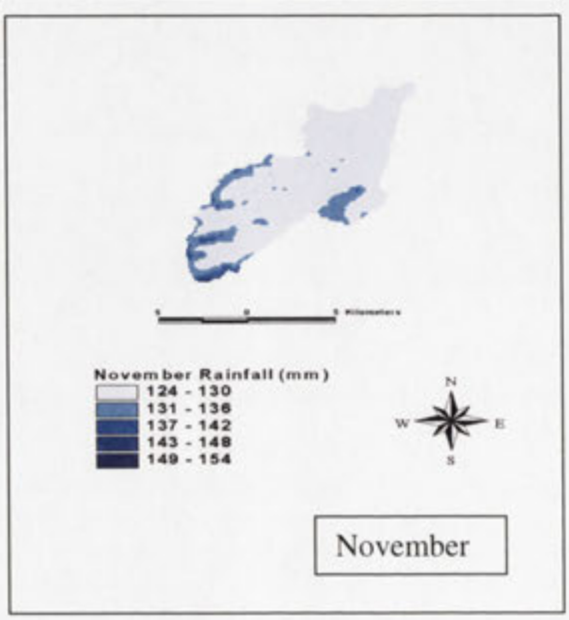


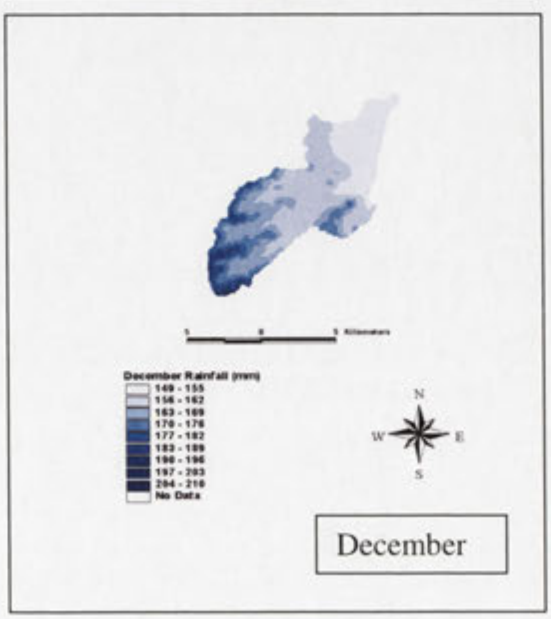

5 0 5 Kilometers
July Rainfall (mm)
102 - 105
106 - 109
110 - 112
113 - 116
117 - 120
121 - 123
124 - 127
128 - 131
No Data
N
W
E
S
July


5 0 5 Kilometers
August Rainfall (mm)
69 - 71
72 - 74
75 - 77
78 - 80
81 - 83
N
W
E
S
August


5 0 5 Kilometers
September Rainfall
60 - 64
65 - 68
69 - 73
74 - 77
78 - 82
N
W
E
S
September


5 0 5 Kilometers
October Rainfall (mm)
106 - 110
111 - 115
116 - 120
121 - 125
126 - 130
N
W
E
S
October


5 0 5 Kilometers
November Rainfall (mm)
124 - 130
131 - 136
137 - 142
143 - 148
149 - 154
N
W
E
S
November


5 0 5 Kilometers
December Rainfall (mm)
149 - 155
156 - 162
163 - 169
170 - 176
177 - 182
183 - 189
190 - 196
197 - 203
204 - 210
No Data
N
W
E
S
December

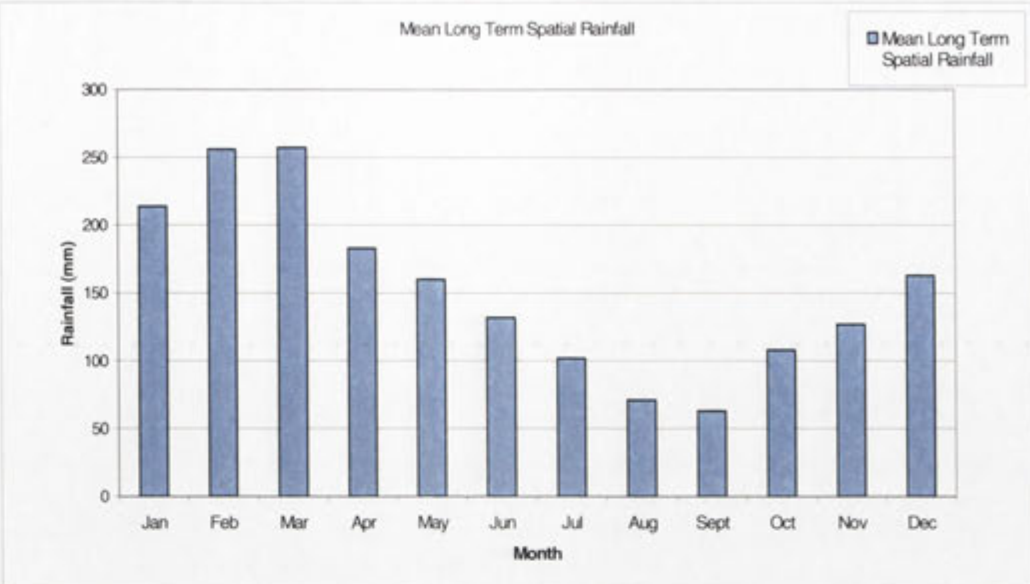


Figure 5.16 Spatially averaged monthly rainfall for the Cudgen Catchment

5.3.6.2 Evaporation

Monthly long-term pan evaporation surfaces (1921-1995) were generated for the Cudgen Catchment using the ANUSPLIN program. The monthly mean spatial pan evaporation for the catchment was determined from the pan evaporation surfaces for each month. Unfortunately, the ANUSPLIN program does not provide a function for determining the annual evaporation surfaces. Therefore the annual spatial evaporation for the Cudgen Catchment was estimated from the monthly mean spatial pan evaporation at 1500 mm. The monthly mean spatially averaged pan evaporation is shown in Figure 5.17. As expected, the pan evaporation is higher during the summer months, with the highest pan evaporation occurring in December during the summer solstice.

Estimating the evaporation from open water bodies can be problematic. This is because the surface energy exchange from a body of water can vary depending on the depth of mixing and the clarity of the water (Grayson *et al.*, 1996). Therefore, pan evaporation readings can differ from one location to the next, with recordings for the eastern coastal zone of Australia as high as 1600 mm per year (Laut, 1971). An annual average value of 1534 mm has been recorded for the coastal town of Kingscliff

(Forsite, 1989) whereas the southeastern Queensland town of Oxenford has an average pan evaporation of 1490 mm (Cook *et al.*, 2002a).

A reasonable determination of the annual potential evaporation (E_p) can be estimated from the pan coefficient (P_{co}) shown in equation 5.1. The potential evaporation for a particular year when the season is wet is given as:

$$E_p = P_{co} + E_{pan} \qquad 5.1$$

Where (E_{pan}) is the pan evaporation. Hoy (1977) computed the annual pan coefficient data for a number of lakes around Australia using energy and water balance methods. He found that the annual pan coefficients varied between 0.66 and 0.92. Lakes or reservoirs within close proximity to the coastal zone had a tendency to give higher readings (i.e, 0.92 for Cataract Reservoir near Sydney, NSW). Seasonal variations probably attributed to the observed variation (Hoy and Stephens, 1977). The Australian Water Research Council recommends a pan coefficient of around 0.7 ± 0.1 for open water bodies (Grayson *et al.*, 1996). Using equation 5.1 and an annual pan coefficient of 0.8 for coastal lakes, the potential evaporation for the Cudgen Catchment was estimated at 1200 mm.

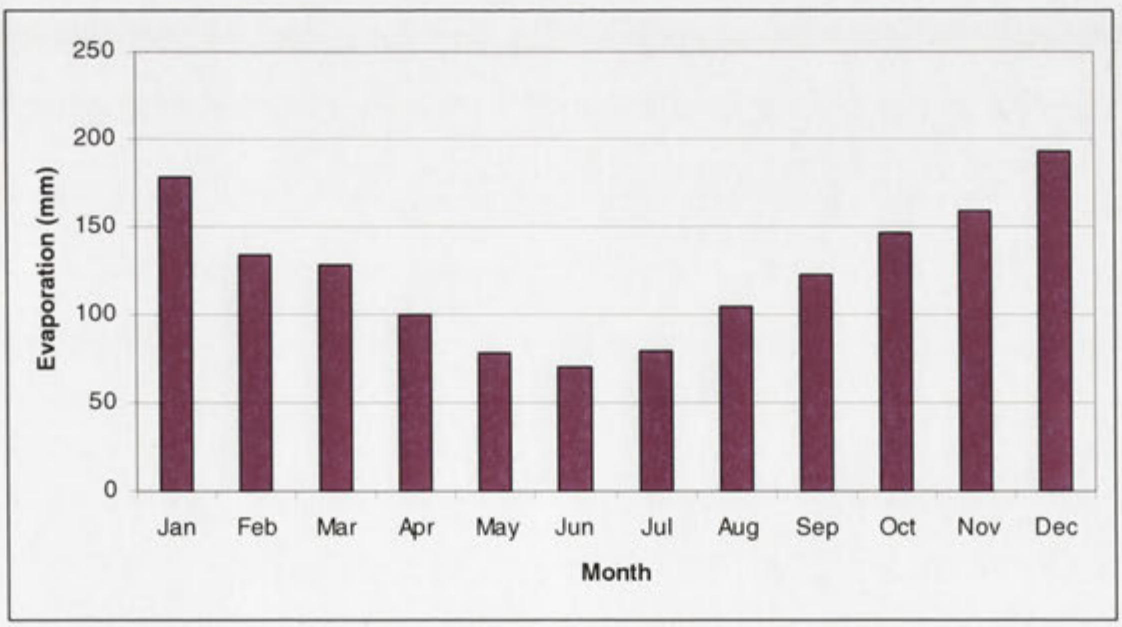


Figure 5.17 Spatially averaged monthly mean pan evaporation for the Cudgen Catchment.

5.3.7 Annual and Monthly Runoff

Annual and monthly runoff coefficients were previously determined (Chapter 4) from both the spatially averaged rainfall and streamflow data for the Uki and Eungella Sub-catchments. A runoff coefficient of 0.31 and 0.32 was determined for the Uki and Eungella Sub-catchments respectively. The Eungella Sub-catchment has a smaller area than the Uki and therefore we would expect the coefficient to be slightly higher since, as a general rule, smaller catchments have higher runoff coefficients than larger catchments. Because the Cudgen Catchment is smaller than the Eungella and less forested, we would expect the Cudgen to have an annual runoff coefficient in the order of 0.32 or higher. Given that all these three sub-catchments of the Tweed are not too dissimilar in size, we would not expect the runoff coefficient to vary significantly between all three catchments (Jakeman, personal communication, 2002). Based on these considerations an annual runoff coefficient of 0.32 was therefore used to determine the annual runoff from annual spatially averaged rainfall for the Cudgen Catchment. For monthly runoff determinations, the runoff coefficients were derived using the long-term (1921-1995) spatially averaged monthly rainfall data for the Cudgen Catchment and the regression equation developed in section 4.2.7 of Chapter 4.

The maximum annual runoff for the Cudgen was estimated to be 770 mm/yr, with the minimum runoff 560 mm/yr (Figure 5.18). The average minium and maximum monthly runoff (mm) for the Cudgen Catchment is shown in Figure 5. 19.

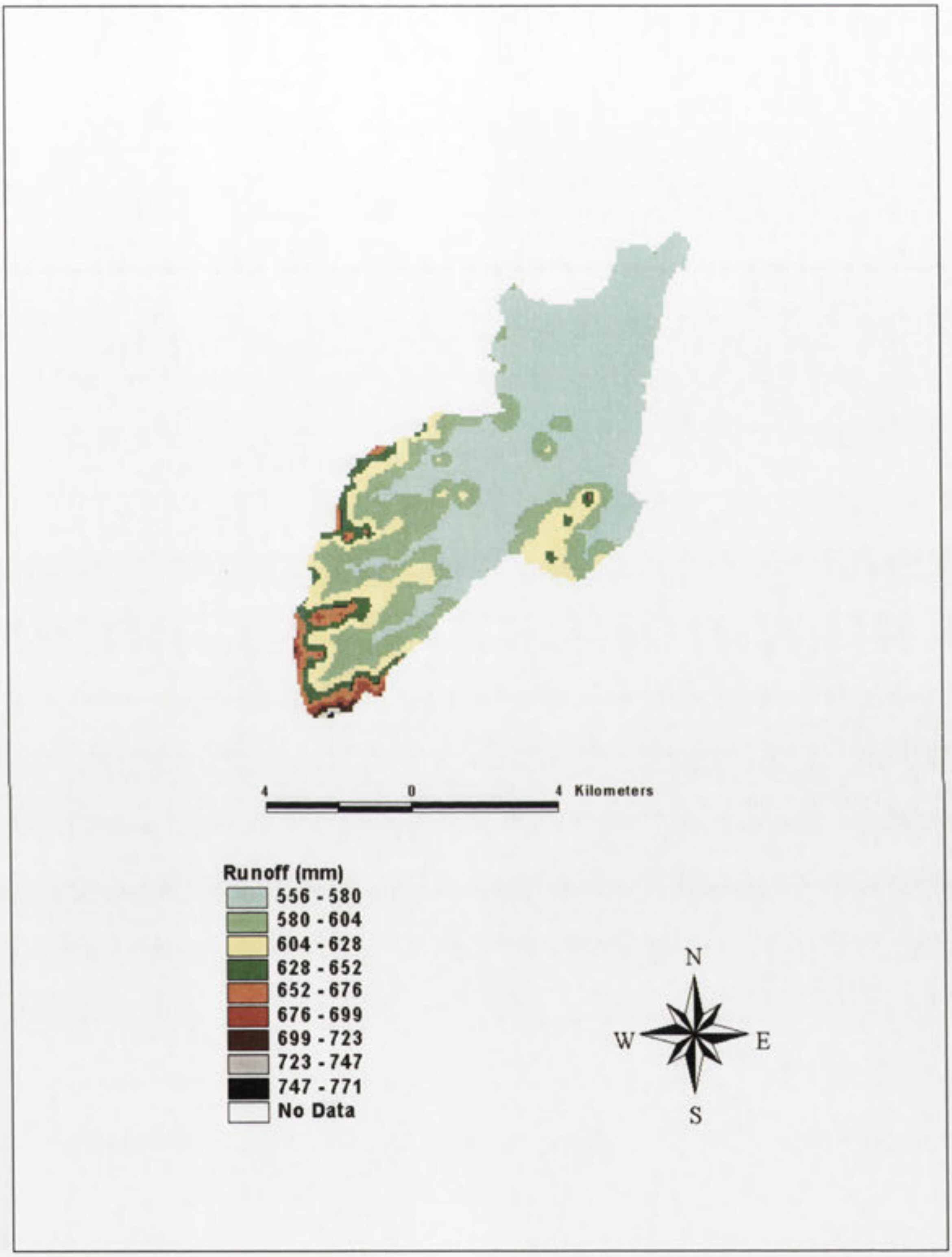


Figure 5.18 Annual runoff grid for the Cudgen Catchment.

The most notable variation in runoff occurs during the summer months. The difference between the minimum and maximum monthly mean runoff diminishes during the autumn to spring period, from the beginning of March to September (Figure 5.19). This trend is consistent with a decrease in rainfall and its variability from March to September (Figure 5.16). The mean runoff for August and September is less than 20 mm, with no significant difference between the minimum and maximum runoff across the catchment.

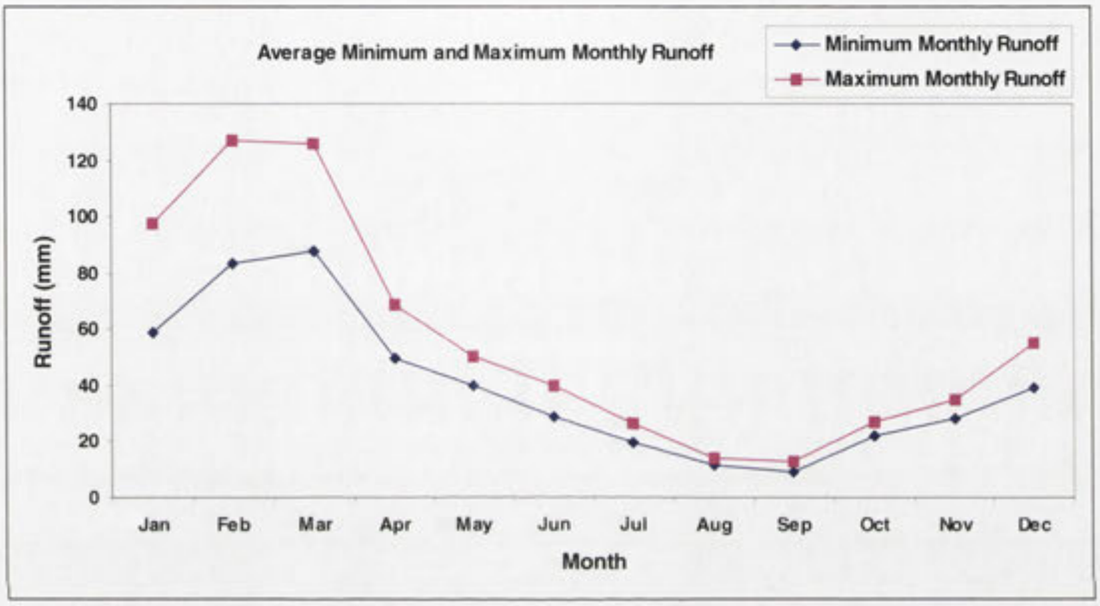


Figure 5.19 Average minimum and maximum monthly runoff (mm) for the Cudgen Catchment.

5.3.7 Annual and Monthly Flows

The annual mean flow for the Cudgen Catchment was determined for both natural, undrained conditions (Figure 5.20) and under agricultural drainage enforcement conditions (i.e, incorporated drainage network, see section 4.2.18, Chapter 4, p108-109) (Figure 5.21). The undrained scenario represents the natural situation prior to human intervention. Under current drainage conditions, approximately 30,000 ML per year of water enters Cudgen Lake from the floodplain to the west of the lake. A total of 37,000 ML of water flows from Cudgen Lake into Cudgen Creek. This represents around 7,000 ML/yr or 20% of the surface water that flows into the lake from the surrounding foreshore and from the township of Bogangar. Modelling the accumulated flow under natural flow conditions (Figure 5.20) produces a similar flow regime.

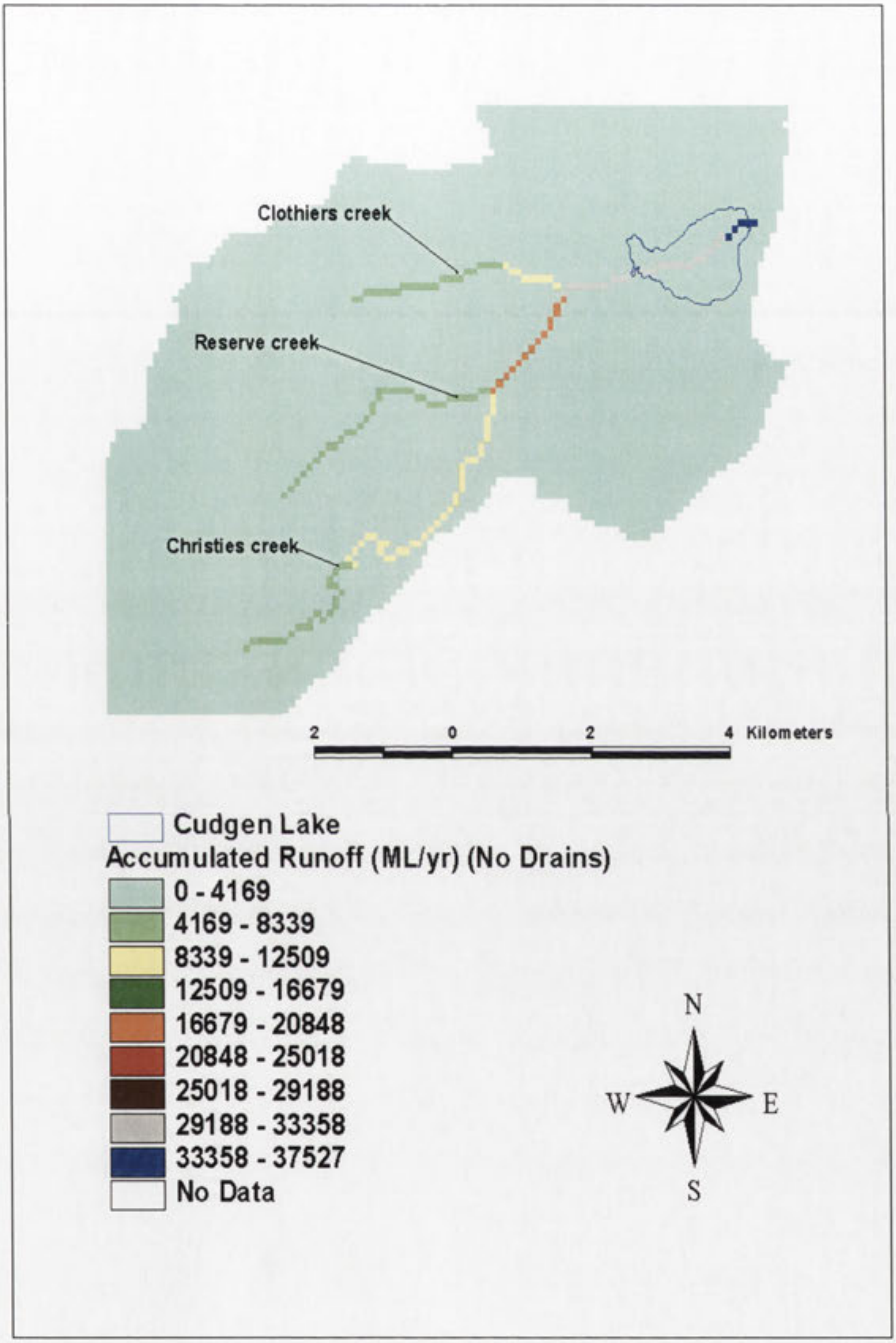


Figure 5.20 Annual flow (ML/yr) with no agricultural drainage enforcement for the Cudgen Catchment.

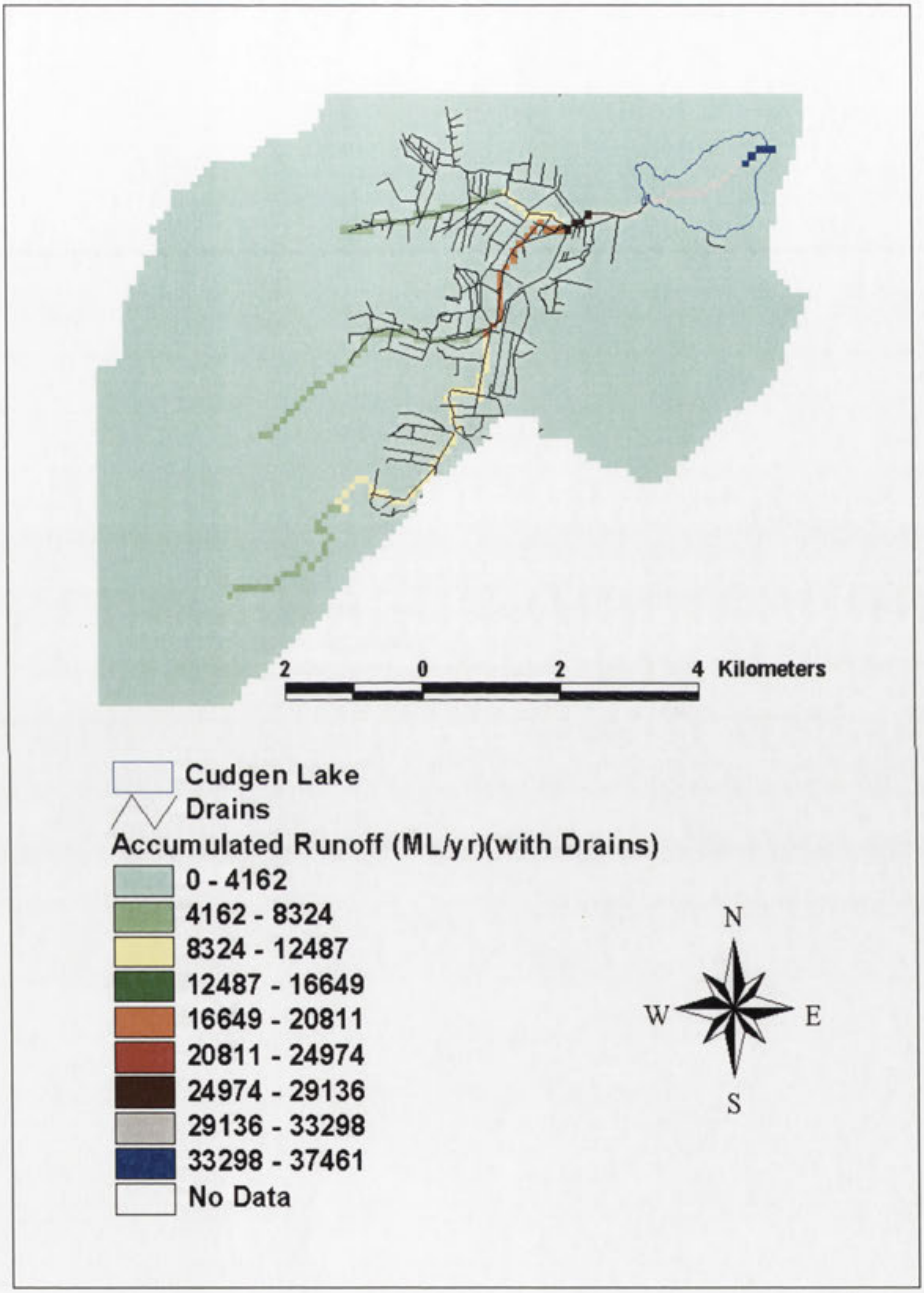


Figure 5.21 Annual flow (ML/yr) with agricultural drainage enforcement for the Cudgen Catchment.

The results clearly demonstrate two important points. Firstly, the impact of human-induced activities, such as drainage works, has had little impact on the total annual flow of surface water entering Cudgen Lake. This is because drains mitigate short-term flooding. Secondly, the modelling results show that most of the surface flow derives from the floodplains of Clothier and Reserve Creeks and from the Christies Creek basin. This modelling observation has significant implications for water quality, given the fact that the floodplains to the west of Cudgen Lake contain oxidised pyritic sediments. It is also evident from the results shown in Figures 5.20 and 5.21 that the constructed drainage system has basically followed the natural drainage paths but has been straightened in some sections. Clearly, there is a major diversion in the natural flow path resulting from these drainage mitigation schemes, at the junction of Clothiers and Reserve Creeks.

The monthly average flows entering and leaving Cudgen Lake are presented in Table 5.4. As expected, the monthly mean flow for the catchment reflects the runoff and rainfall trends, with February having the highest monthly mean flow of 47,870 ML and September the lowest flow of 5,120 ML.

Table 5.4 Monthly accumulated flows entering and leaving Cudgen Lake.

Month	**Flow (In) ML**	**Flow (Out) ML**
January	35,550	42,630
February	47,870	57,560
March	47,490	57,340
April	26,530	32,140
May	20,850	25,450
June	15,420	18,790
July	10,390	12,640
August	6,040	7,390
September	5,120	6,230
October	11,340	13,770
November	14,550	17,680
December	22,200	26,740

5.4 Impact of Rainfall and Drainage on Acid Outflows

5.4.1 Introduction

The degree of runoff and hence the amount of acid that is discharged into aquatic ecosystems will depend largely upon the amount of rainfall. However, as discussed in Chapter 4, runoff is also influenced by the height of the watertable. During periods of heavy rainfall, significant surface runoff will occur when the watertable reaches the soil surface. Previous research into the associations between water quality, hydrology and climate factors, where acid sulfate soils are present, has shown that acid discharge events are not entirely dependent on the amount of rainfall (Wilson *et al.*, 1999). The position of the watertable and the available water storage capacity of the soil are important factors determining an acid outflow event. The translocation of acid and other oxidation products through the soil profile is controlled by the rise and fall in the watertable which in turn is controlled by evapotranspiration from deep rooted crops, such as sugar cane (White *et al.*, 1997). The movement of water from the soil to the drainage system takes place when the watertable level rises above the water elevation of the drainage system (Wilson *et al.*, 1999). As watertable levels rise there is lateral movement of acidified water into the drains as well as vertical flow through the soil profile to the soil surface. For this reason it can be argued that the modelling of acid discharge should also take into consideration the groundwater dynamics in response to rainfall frequency and intensity. The modelling concept developed here is concerned primarily with surface water flows when the watertable is elevated.

5.4.2 Modelling Acid Outflow Events

The hydrological modelling carried out in this section used the average monthly and annual flows determined in section 5.3.8 and sulfuric acid land loads to calculate the extent of acid discharge under both natural and current drainage regimes. The hydrological model was therefore used to ascertain the impact of the drainage network (i.e, agricultural drainage enforcement, see section 4.2.18, Chapter 4) on the transportation of acid in response to the annual flow. As a comparison the impact of acid transport and distribution under the natural conditions (i.e, without agricultural drainage enforcement) was also modelled. The model was also used to calculate the annual and monthly accumulated sulfuric acid concentrations. For this section the model assumes a high watertable level and did not consider the small tidal influences and its impact on the lake and drainage water quality. Furthermore, the model did not take into account the impacts of individual rainfall events on acid discharge.

Figures 5.22 and 5.23 shows what we might expect, in terms of sulfuric acid transportation and distribution within the lower floodplain, under natural drainage conditions (i.e, no human-made drains) and under agricultural drainage conditions, respectively. The annual concentration of acid derived from the modelling results is in mg/L. There is a clear distinction in the location and distribution of sulfuric acid between the natural undrained condition (Figure 5.22) and the agricultural drainage condition shown in Figure 5.23. From these results, it is apparent that the drainage network has had a major impact on the transportation of acid from the floodplain to the drains. This is in contrast with the natural drainage condition in which the distribution and location of the acid is primarily contained within the floodplain (Figure 5.22).

The drainage network allows the rapid removal of surface water from the flood plain. Water moves much more quickly though a drainage system because of the gradients and hydraulics involved than it does over an area that is perpetually flat. Therefore, the drainage system not only acts as a potential reservoir for acid, but also is a conduit for the transportation of acid to Cudgen Lake. Under natural floodplain conditions the surface water remained confined to the land, moving only slowly from the floodplain to the lake. Drainage schemes have substantially shortened the residence time for surface waters, thus increasing the rate of surface water movement from the floodplain to the streams and other aquatic ecosystems (White *et al.*, 1999a).

The results obtained here clearly reinforce the current belief that where there are agricultural drains situated on acid sulfate soil landscapes then remediation strategies must be aimed at treating the problem at the drainage level (Waite *et al.*,2003). Clearly, there is some merit in modelling the effects of reducing the number of drains or to examine the impacts of changes in drainage design on the transportation of acid to Cudgen Lake. In Chapter 8, the effects of drainage remediation strategies on reducing acidification of Cudgen Lake is examined and modelled in more detail.

From the model, the annual concentration of acid measured at the entrance to the lake is around 13 mg/L for both the drained and undrained situation. Thus the total concentration of acid entering the lake is the same when averaged over a one year period regardless of whether drains are present or not. Similarly, the amount of acid leaving the lake is also around the same concentration for both drained and undrained scenarios. The residence time for surface water under natural or backswamp areas has changed from around 100 days to around five days under well-drained conditions (White *et al.*,1999a). Under the natural undrained backswamp conditions, most of the surface water would have evaporated in dry times but now with the advent of drainage systems, it is exported directly to the lake environment.

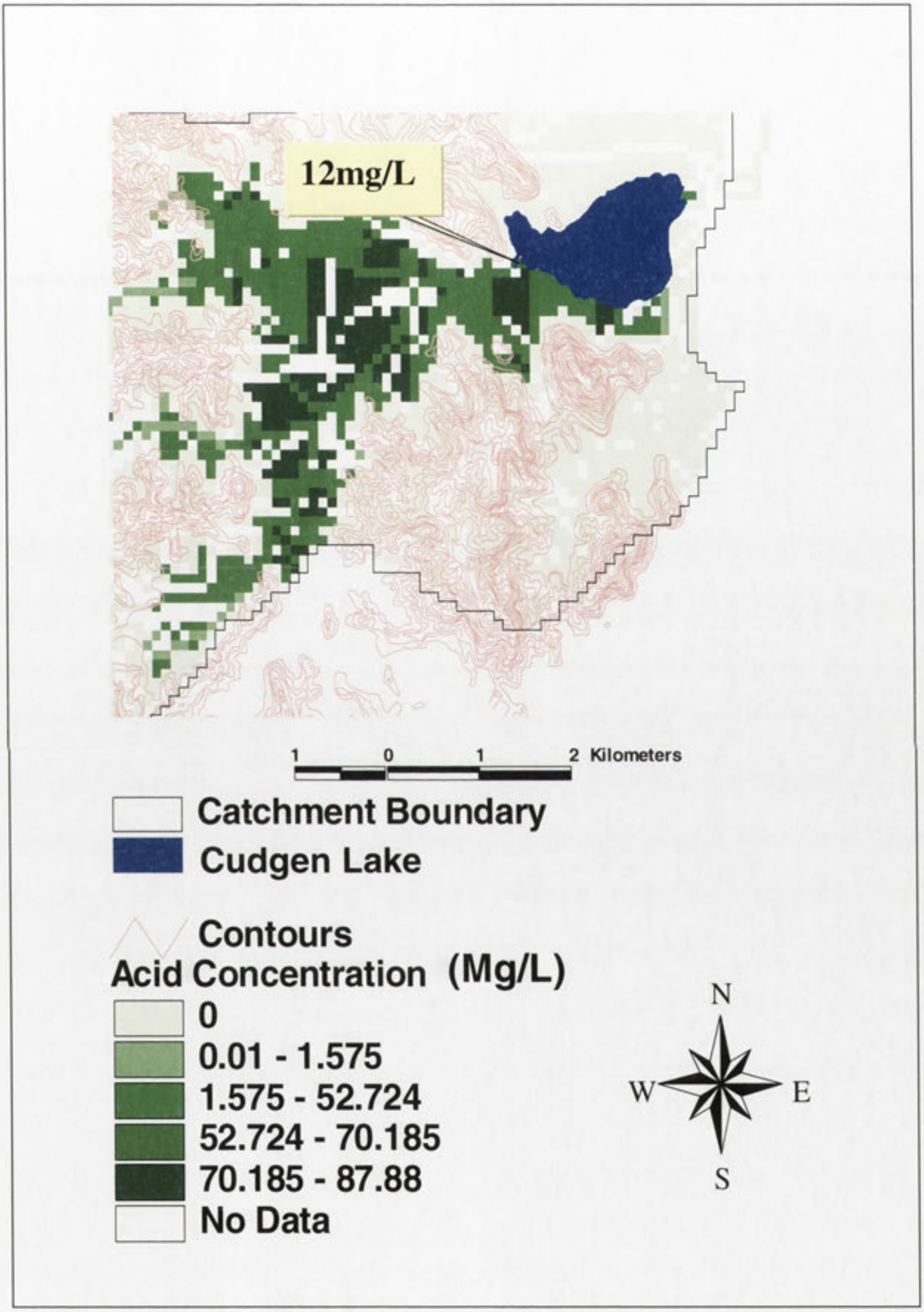


Figure 5.22 Annual sulfuric acid concentration mg/L in surface water under natural drainage conditions.

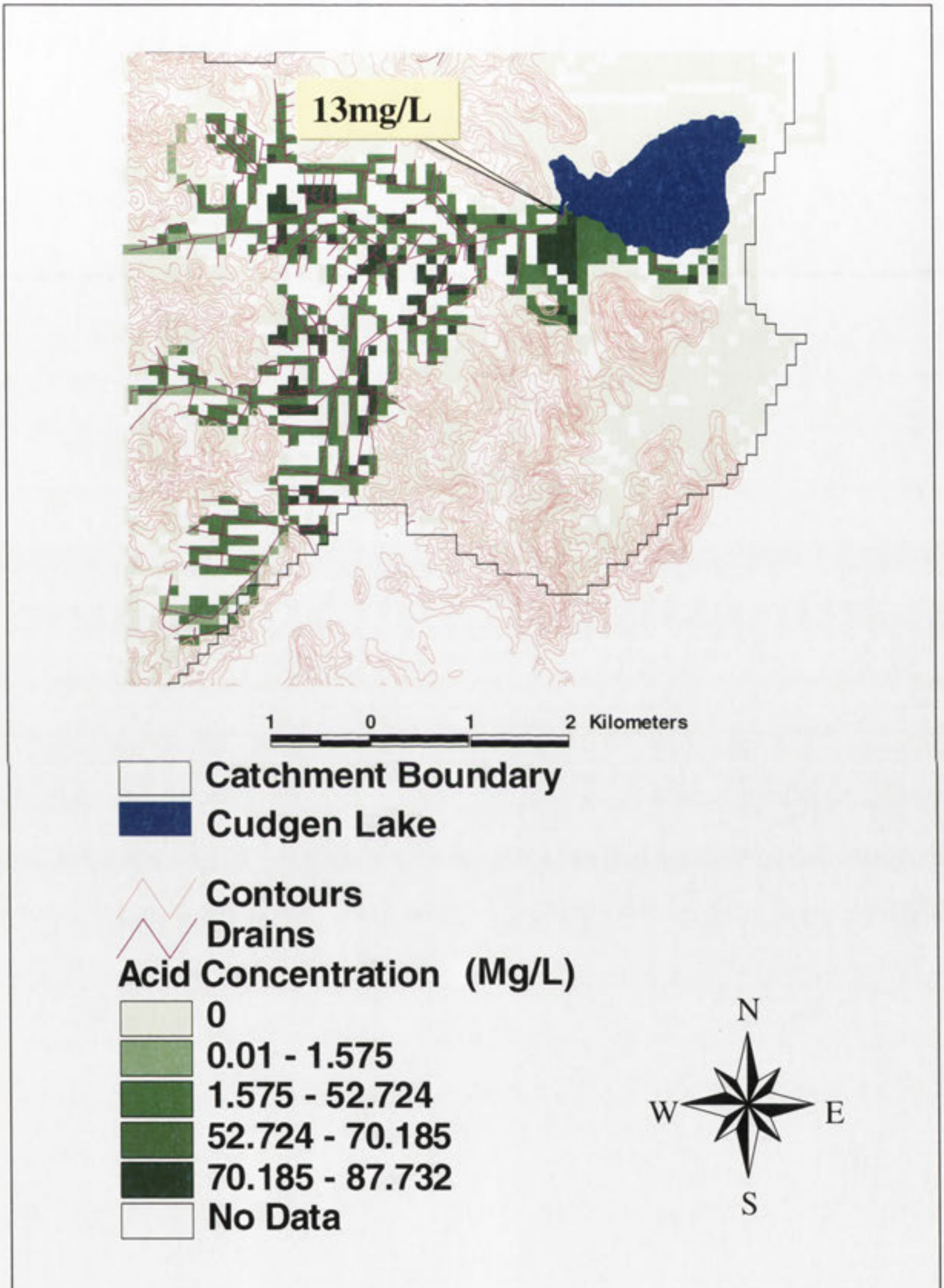


Figure 5.23 Annual sulfuric acid concentration (mg/L) in surface water under agricultural (artificial) drainage conditions.

5.5 Water Quality Results

Water quality testing has taken place extensively in the Cudgen Catchment at various times by different organisations (Tulau, 1999a). Despite the degree of testing carried out at different periods over the last 20 years there has been no real continuity with respect to the collection of water quality data and there are large gaps in the monitoring data for some monitoring sites. However, extensive water quality testing has been conducted by the Tweed Shire Council (TSC) after the 1991 fish kills (Easton, 1991) with monitoring occurring at two main sites in Cudgen Lake and at five drainage sites. Detailed data are also available before and after the last major fish kill on 18 August 1998. Monitoring results (M.Tunks, personal communication, TSC, 2001) showed high levels of acidic ion species including aluminium with concentrations as high as 60 ppm and pH values as low as 2.5 in the drainage water. Lake water monitoring also revealed pH levels on average between 3.9-4.8. The water quality results presented in this section are for the period 1991 to 1998. This period includes the 1991 and 1998 fish kills, when significant acid outflow events occurred. Water quality results for this period were compared with rainfall records from individual weather stations at Banora Point and Murwillumbah. These baseline studies will be used in Chapter 7, section 7.5 to determine a relationship between streamflow and discharge.

5.5.1 Water Quality Monitoring Sites

Drain water quality was monitored at seven main monitoring locations (T1,T2,T3, T4,T4A,T5 and T6) within the drainage system (See Figure 5.24). Drain water quality was measured for pH, electrical conductivity, and water level. Lake water quality was measured at two main locations in Cudgen Lake. Electrical conductivity and pH were recorded at Scout Camp and at PWD for surface and depth. Figure 5.24 shows the locations of the drain and lake water quality monitoring sites. Scout Camp monitoring site is located at the eastern end of the lake, a short distance from the entrance to Cudgen Creek. PWD is located at the southern end of the lake. The monitoring sites T1, T2, T3, T4, T4A, T5 and T6 are located on the main drainage lines. Some of the drainage sites are only accessible by four wheel drive vehicle which made recording difficult during certain times of the year. The monitoring sites T1, T2 and T3 are located at the junctions between the drain lines and Round

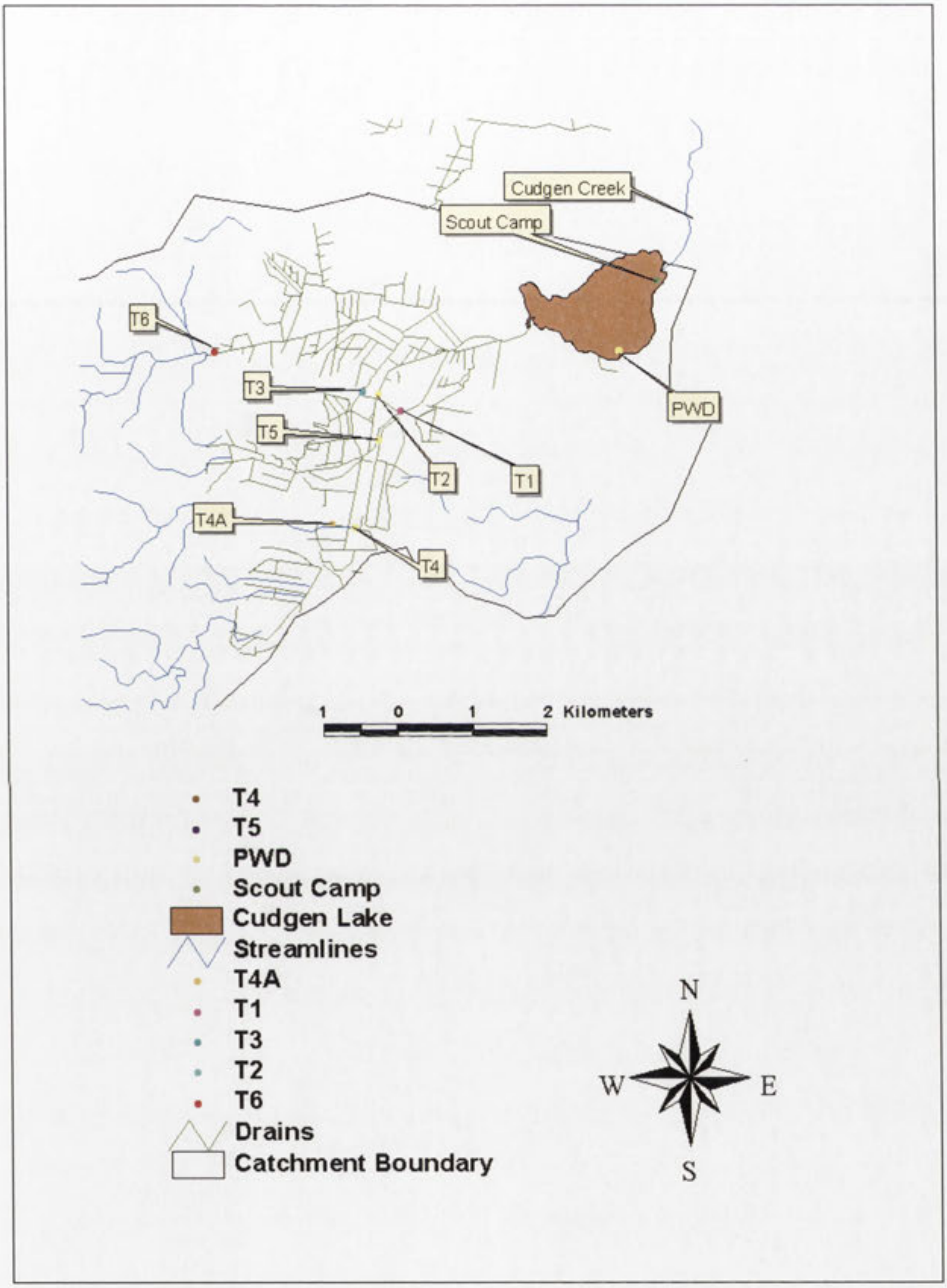


Figure 5.24 Drainage Network and monitoring sites for the Cudgen Catchment.

Mountain Road and are easily accessible by car. The monitoring site T2 is located on the main drainage line leading into Cudgen Lake. This drain takes most of the flow from Christies and Reserve Creeks.

5.5.2 Drain Water Quality

Drain water quality for the year 1998 was measured at regular intervals throughout the year. The mean spatial rainfall for 1998 showed monthly rainfall data that were either below or above average for the catchment (Figure 5.25). Dramatic changes in pH, water level and electrical conductivity were also observed during 1998. Figure 5.26 shows the drain pH for the monitoring sites T2, T3 and T4A and figure 5.27 compares drain water level with pH for the period January to November 1998 for monitoring sites T1, T2, T3, T4 T5 and T6. Figure 5.27 also shows electrical conductivity for the same time period and for the same monitoring sites.

An examination of these water quality results shows that the most notable change in water quality occurred during the month of April when above average rainfall affected drain water quality at all monitoring sites except T6. The monitoring site at T6 is located at the junction of Clothiers Creek and the Clothiers Creek drainage system. The water quality at this site changes very little with respect to rainfall activity. This site is also located in a region containing acid sulfate soil layers to a depth of 2 metres.

The spatially averaged rainfall results for the months of January, February and March were well below the average for this period (Figure 5.25). Drain water pH had remained high for these months at all monitoring sites with a correspondingly low drainage water level (Figure 5.27). On closer inspection, a gradual rise in drain water level was observed for the monitoring sites T1, T2, T3 and T4 during February and March, however, pH values remained fairly static rising only slightly by one pH value. A noticeable decline in pH was recorded for the month of April (Figure 5.26) which coincided with a high monthly mean rainfall of approximately 250 mm (Figure 5.25). The mean spatial rainfall record for this month was well above the average monthly spatial rainfall for April of approximately 180 mm (Figure 5.25). Examination of the daily rainfall and monitoring events revealed a sudden pH drop occurring on the 15th April and a heavy rainfall event of 104 mm recorded on the same day at Banora Point (See Figure 5.29, p163). This amount of rainfall was more than half the spatially averaged rainfall for the month of April. Smaller rainfall events also occurred on the 16, 17 and 18 th April.

The monitoring results in Figure 5.27 showed that from January 27 to November 4 1998, pH values were as high as 7.8 and as low as 2.8. It can be seen that pH fell following the rainfall event that occurred on the 15th April, but water levels did not show any dramatic rise despite the magnitude of this rainfall event. A dramatic rise in water level was, however, observed at some of the monitoring sites on 27th April following another rainfall event. Clearly, this event filled up any remaining soil storage capacity.

The high pH values recorded during the summer months, in association with the low drainage water levels, suggests that the amount of rainfall that fell prior to these large rainfall events (i.e, January to mid April) had little or no effect on drainage acidification, but rather filled the water storage capacity of the soil. Clearly, during these drier periods there would have been an accumulation of sulfuric acid within the soil profile. The rainfall events of April were of sufficient magnitude to result in the mobilisation of stored acid from the soil into the drainage system.

The events that occurred during 1998 can be explained in terms of the dynamics of the watertable. When the water level in the drainage system is lower than the watertable level, there is a lateral movement of water into the drains. When the water levels in the drains are higher than the surrounding watertable a negative gradient is produced, resulting in no lateral movement of water through the soil profile to the drainage system. Sugar cane crops and other plant crops control the height of the watertable through the process of evapotranspiration, thus maintaining a low watertable (White *et al.*,1997). Where there are very few crops, as is the case for the Cudgen Catchment, the amount of rainfall would play a significant role in the overall magnitude of a rise in the watertable level. From previous studies (Wilson, 1995), when the watertable is low and the soil unsaturated, there is a high soil water storage capacity resulting in little or no surface water runoff.

Although it is fairly certain that there would have been some lateral movement of acidic groundwater into the drainage network, the initial large rainfall events in April appeared to be of insufficient magnitude to result in translocation of acid into surface waters. The dry months leading up to the 15th of April, appear to have produced a large soil water deficit and low watertables, so that surface water runoff did not occur. Rainfall events following 15th April were of sufficient quantity to result in surface runoff into drains, as evidenced by the dramatic rise in drainage water levels on 27th April, when further rainfall had taken place.

The electrical conductivity (EC) records for drain water during 1998 are shown in Figure 5.27. For the monitoring sites T1 – T6 a jump in EC was recorded prior to the April 15th rainfall. This spike in EC may have been due to the occurrence of a king tide which would have resulted in an intrusion of sea water into the drainage system from the lake. A rise in water levels was also apparent at this time and there were correspondingly high EC levels recorded in Cudgen Lake at PWD and Scout Camp. Salt water intrusion from the ocean often results in the migration of fish populations upstream into the drainage network, where they can often become trapped behind floodgates (Sammut *et al.*,1993; 1996). When the drainage system is not under tidal influence EC increases exponentially with a decrease in pH (Figure 5.28). At very low pH levels (pH 2-3), EC readings rise rapidly. A change in pH from 3 to 2.5 results in around a three fold increase in EC (Figure 5.28). This increase in EC is due to the export of soluble acidic products, such as aluminium and iron.

Below average rainfall returned to the catchment during the months of June and July (Figure 5.25). A small rise in pH was accompanied by a lowering in drainage water levels at most monitoring sites. Despite a slight rise in pH, levels remained fairly low (pH 4-5) and did not return to the levels previously recorded prior to the 15th of April (pH 6-7). Following this short period of dry weather during June and July, further above average rainfall occurred during the month of August (figure 5.25). Two major rainfall events occurred during this month, one on the 6th August with 56 mm recorded at Banora Point and another on the 27th of August (68mm). It is interesting to note, that no rainfall was recorded at Murwillumbah during this period. The rainfall event on the 6th of August did not result in any substantial change in pH levels in the drain water. Although this rainfall event was not as extensive as the event that occurred on the 15th of April, it had a much greater impact on the quality of the lake water, which will be discussed in the next section.

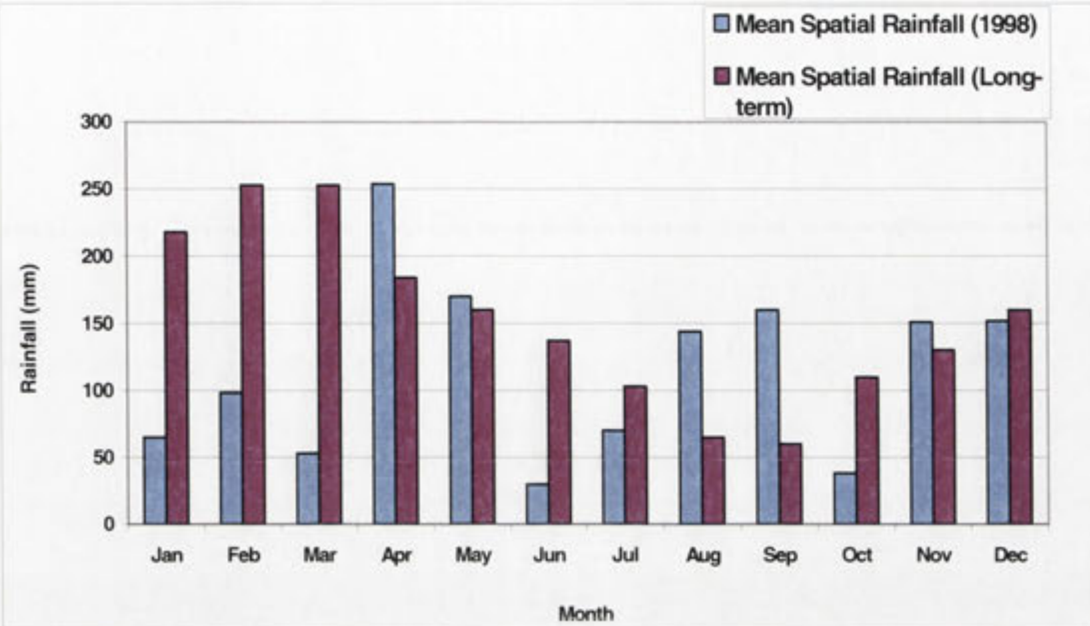


Figure 5.25 Monthly mean spatially averaged rainfall for Cudgen Catchment for the period January to December 1998 compared with spatially averaged long-term rainfall for the Cudgen Catchment.

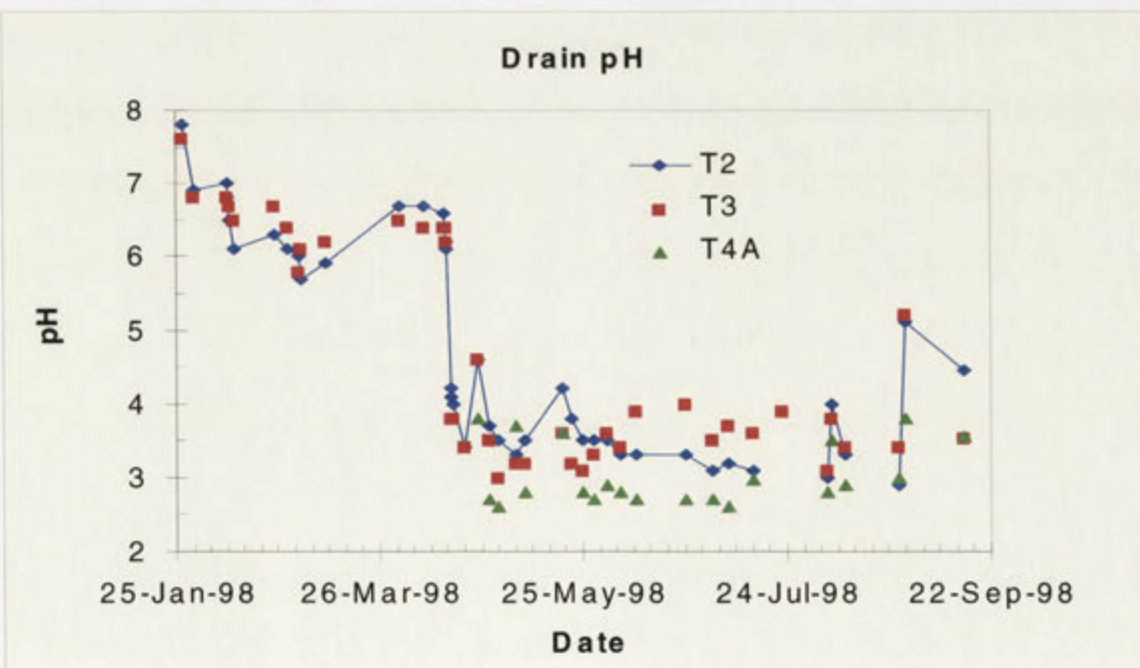
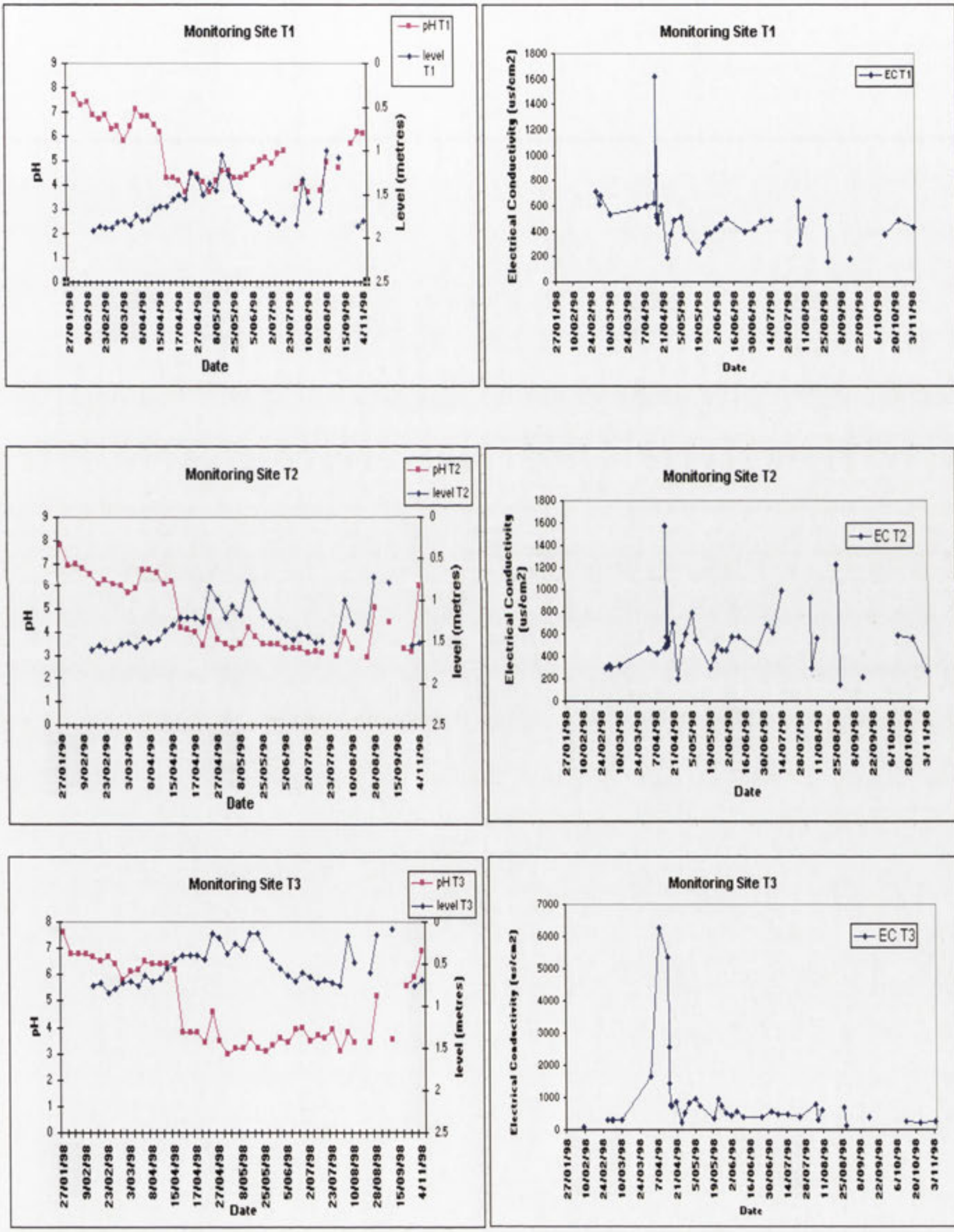
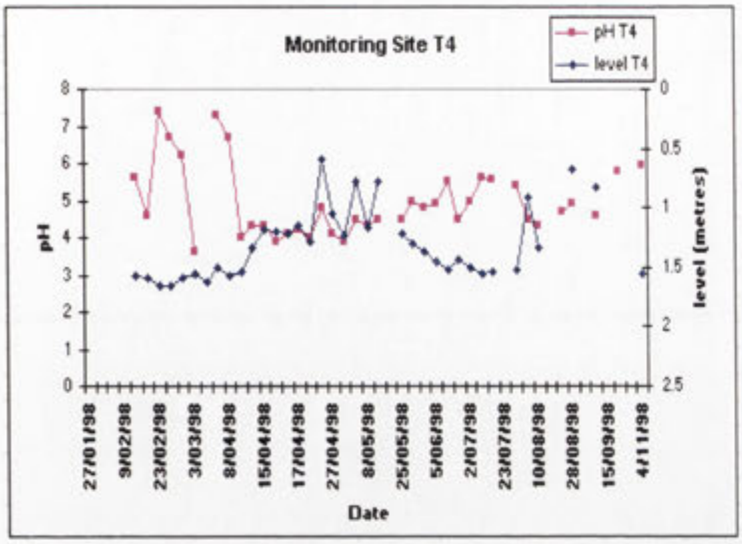
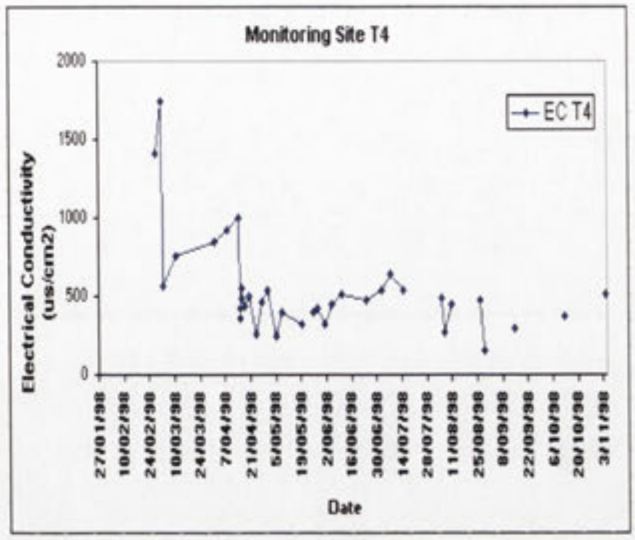


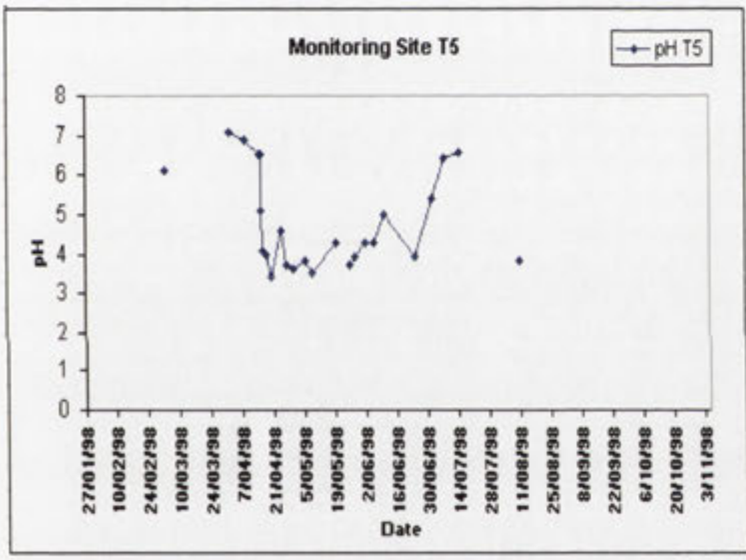
Figure 5.26 Drain pH for the monitoring sites T2, T3 and T4A for the period January to September 1998.

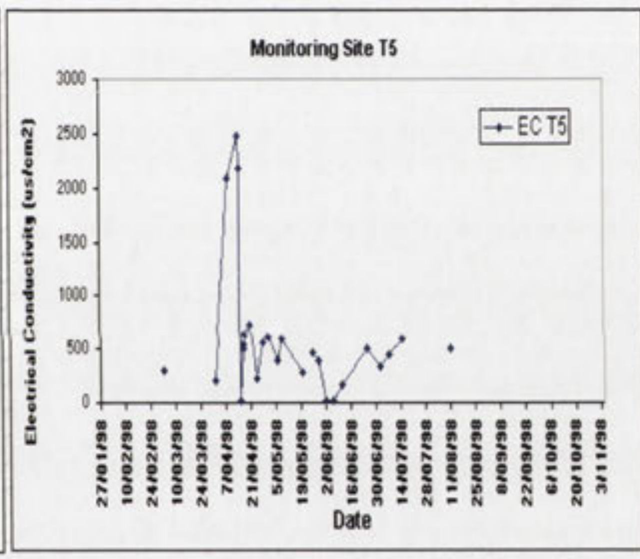
Figure 5.27 Drain water quality results for water level, pH and electrical conductivity. Water levels were measured from a base height at the top of the drains.

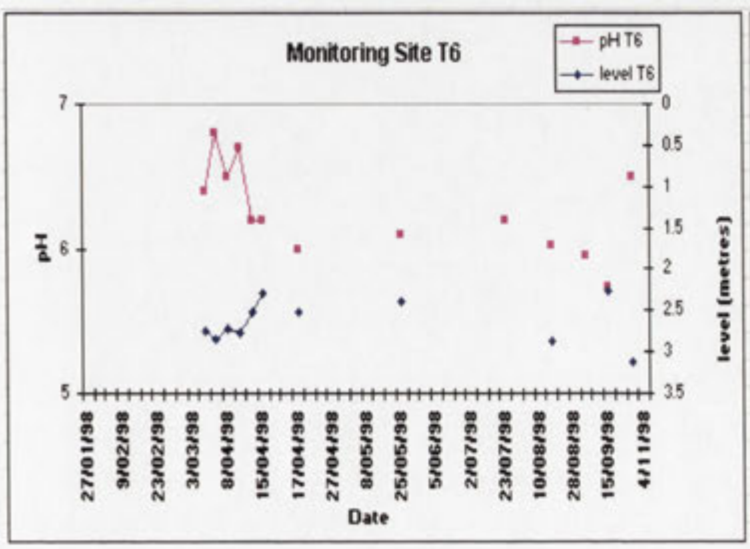


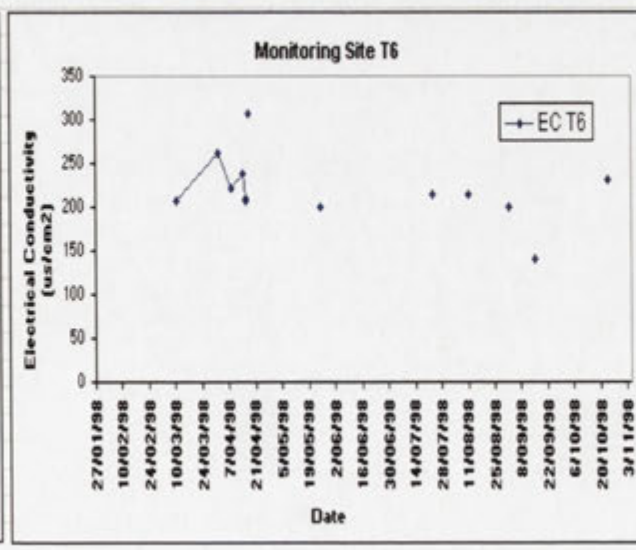

Monitoring Site T4
pH T4
level T4
pH
level (metres)
Date


Monitoring Site T4
EC T4
Electrical Conductivity (us/cm2)
Date


Monitoring Site T5
pH T5
pH
Date


Monitoring Site T5
EC T5
Electrical Conductivity (us/cm2)
Date


Monitoring Site T6
pH T6
level T6
pH
level (metres)
Date


Monitoring Site T6
EC T6
Electrical Conductivity (us/cm2)
Date

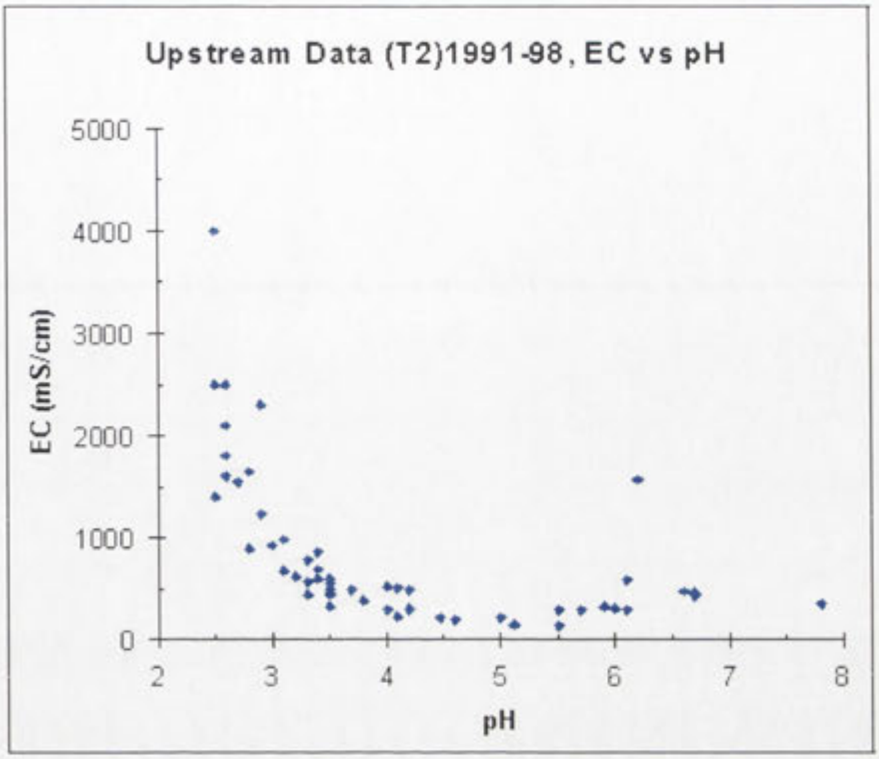


Figure 5.28 Electrical conductivity versus pH for drain water.

5.5.3 Cudgen Lake Water Quality

The water quality of Cudgen Lake is generally poor, with a history of low pH and high aluminium levels well in excess of the ANZECC guidelines (WBM Oceanics Australia, 1998). Furthermore, it has also been shown that the brackish-saline waters lying below the surface waters are generally less acidic but often have a low dissolved oxygen content (WBM Oceanics Australia, 1998). Figure 5.30 shows the water quality results for Cudgen Lake from the 17th of April to the 4th of November 1998. On the 18th of August 1998 a major fish kill occurred resulting in the death of around 45,000 fish in Cudgen Lake (Easton, 1992).

During 1998, pH levels recorded below the surface waters remained between pH 5 and pH 7.2, and included a much more significant change which occurred during August, for all the monitoring sites - at surface and sub surface levels. It is interesting to note that although drain water pH fell to around pH 4 on 15th April after a heavy rainfall event, lake water pH remained high at pH 7.2 falling to an average pH value of 4.9 on the 24th April. The pH values at depth remained above 5.5 (Figure 5.30). Based on these results, it would appear that the surface water flows were insufficient to have any immediate impact on the water quality of Cudgen Lake and that the small tidal exchange appeared to be effective at neutralising the acid originating from these low surface flow events. This observation supports the previous notion that watertable levels were not high enough to produce sufficient surface acid groundwater discharge. However, rainfall events occurring after this date, had some impact on lake water quality with pH values falling to around 5.5 for PWD (depth) and 5.0 for PWD (surface). Scout Camp recorded a much lower pH value of 4.2 at the water surface and pH 5 below the surface. This appears to be due to the displacement of drain water into the lake.

The distribution of pH readings throughout the lake varied quite significantly up until the 10th of August, with some regions and depths experiencing lower pH levels than others. The pH levels at all locations and depths dropped below 5.5 and continued to fall to below 4.5 following subsequent rainfall events during this month. It is apparent that the rainfall event on the 6th of August (56mm) (Figure 5.29) was of sufficient quantity to initiate sufficient acid water flows through the drainage network. The fish kill event took place on the 18th August, 8 days after the first initial drop in pH from 6.3 to 4.9. It would appear that fish populations continued to survive for this short period at low pH. Fish are able to avoid highly acidic waters and it may have been, that pockets of better quality water were finally acidified after this time.

Unlike drain water pH, lake water pH levels had a much better recovery during the months of June and July with pH readings returning close to the readings recorded on the 24th of April. The increase in conductivity during April, June and July (Figure 5.31) was probably due to salt water intrusion from the ocean which would have had a buffering effect on acid inflow. Because of the poor tidal exchange, the buffering capacity of the lake by sea water is relatively low (White and Melville, 1993; White and Melville, nd). Both electrical conductivity and pH levels dropped significantly during August for both PWD and Scout Camp at depth and surface (Figures 5.30 and 5.31). The relationship between pH and electrical conductivity for lake water is shown in Figure 5.31. As sea water intrusion occurs (high EC), the neutralisation of acid occurs also. In the drains, higher EC's occur at low pH's due to the export of soluble acidification products such as aluminium and iron. Figure 5.33 shows the relationship between pH and soluble ions, aluminium and iron. A decrease in pH results in an increase in the solubility of ions, including aluminium and iron.

The monitoring results for lake water provide a greater insight into the relationship between rainfall and its impact on water chemistry. Although water quality is greatly influenced by rainfall, the magnitude of a rainfall event may not have an immediate impact on the water chemistry for Cudgen Lake. The water storage capacity of the floodplain soil and the watertable height had a significant impact on the rate of flow and acid discharge during this period. This explains why a single large rainfall event during April 1998 did not have any immediate impact on the pH of Cudgen Lake. The rainfall data revealed that below average rainfall was recorded during the summer months prior to the April rainfall events, which would have contributed to low watertables. The climatic conditions leading up to the major acidification event during August 1998 had a significant role in determining water quality.

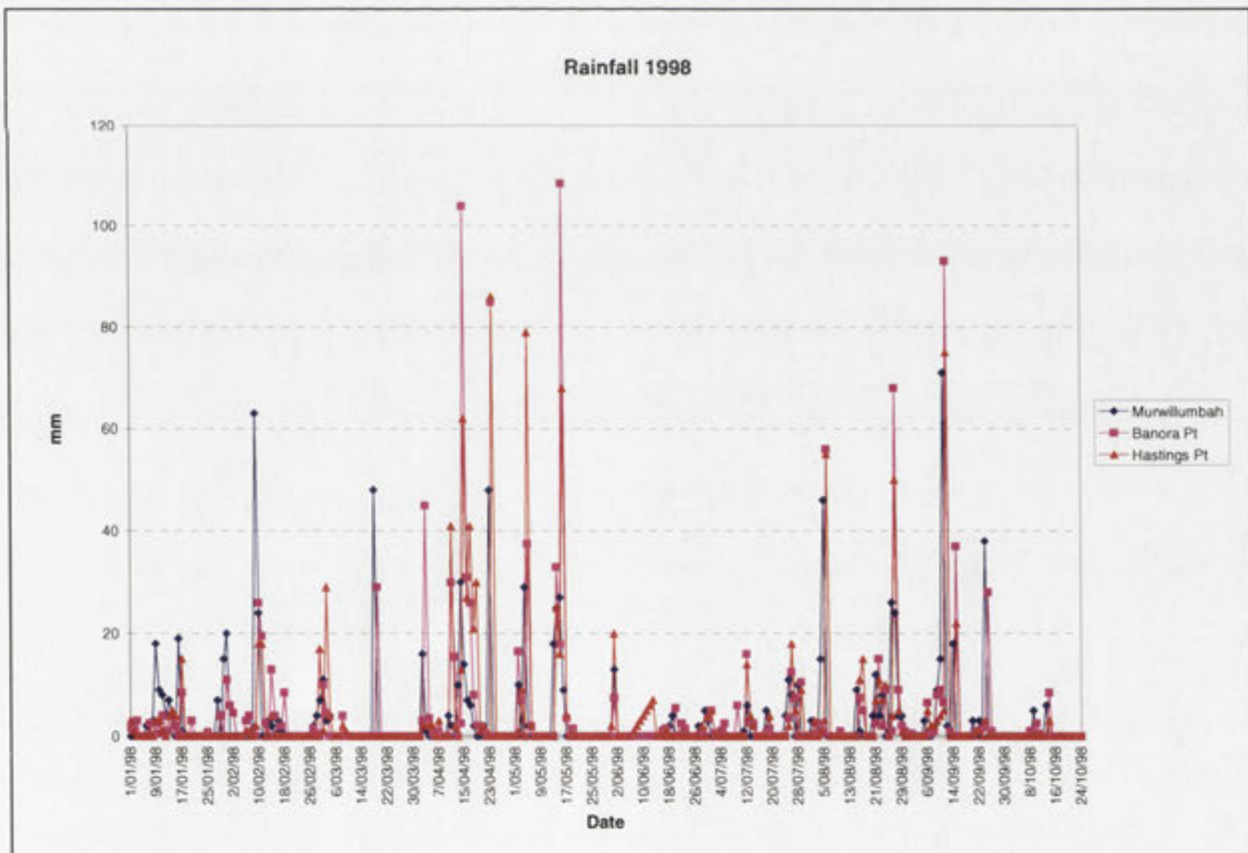


Figure 5.29 Individual rainfall records for Murwillumbah, Banora Point and Hastings Point.

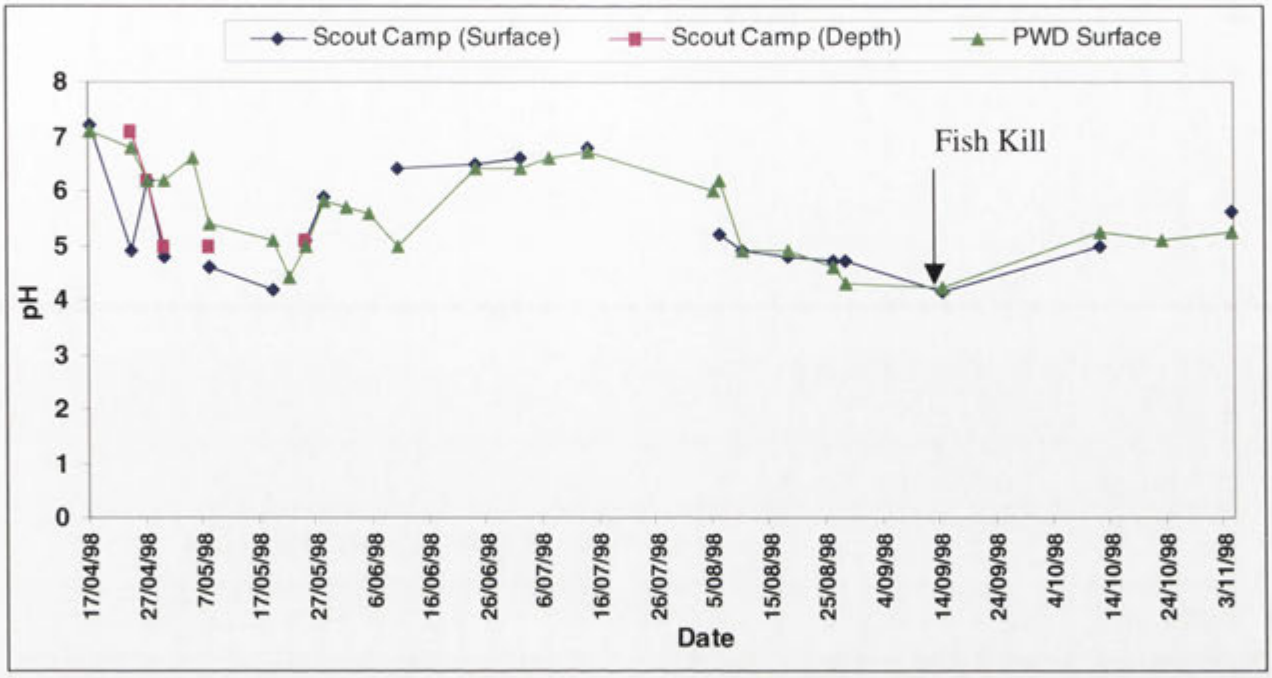


Figure 5.30 Lake water pH for the period 17th of April to the 4th of November 1998.

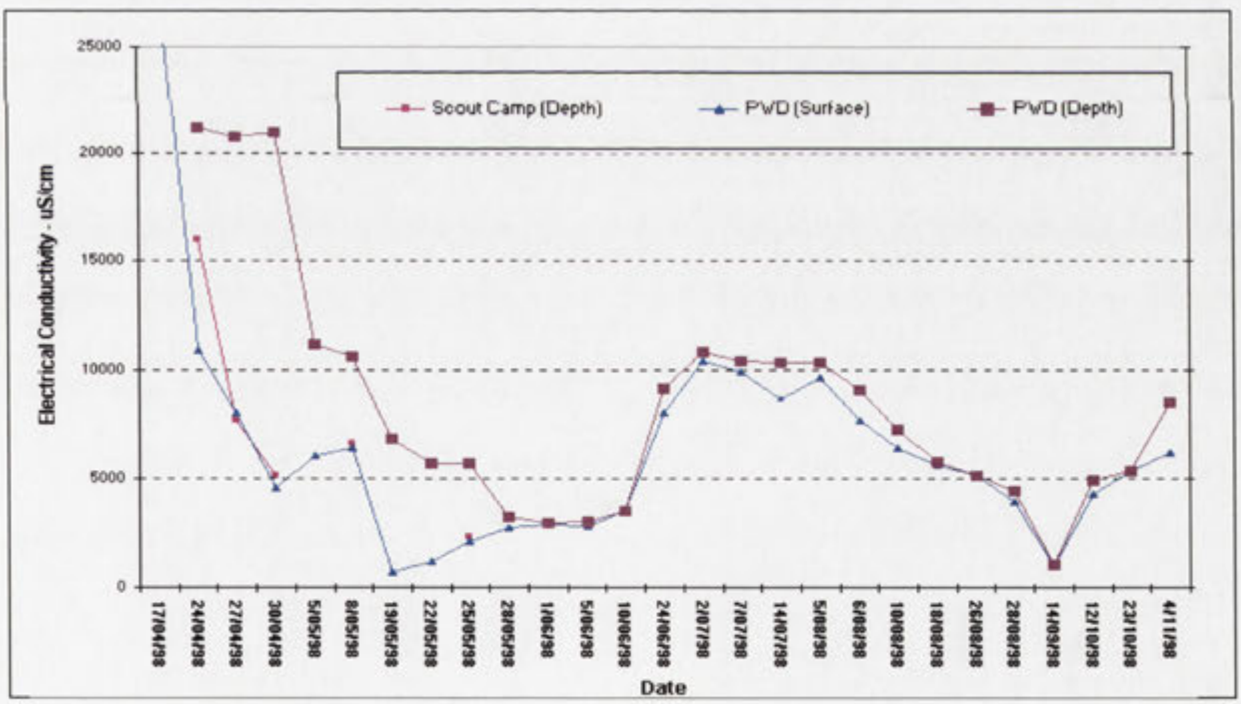


Figure 5.31 Electrical conductivity in Cudgen Lake for the period 17 April to 4 November 1998.

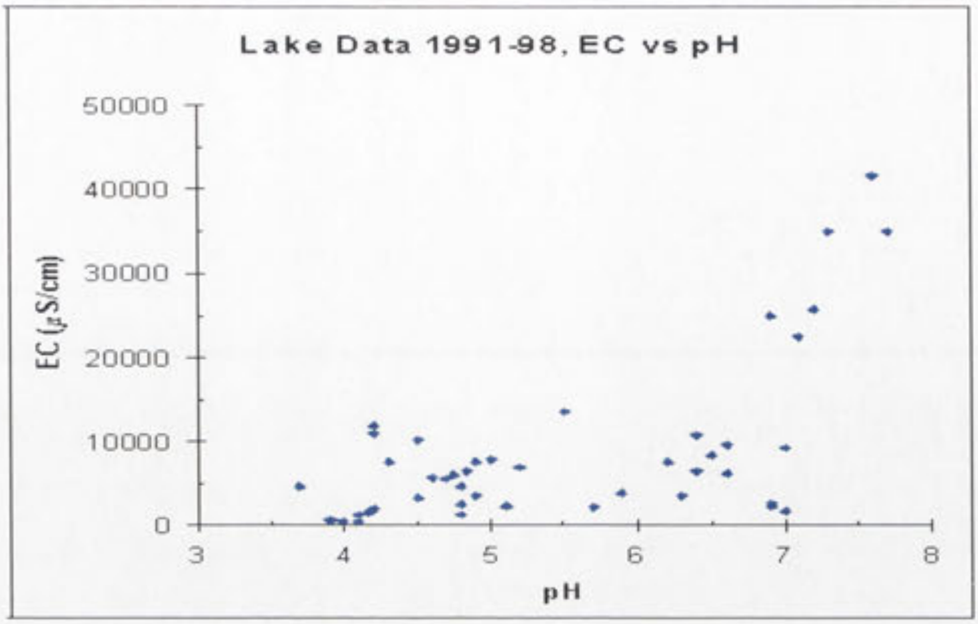


Figure 5.32 Relationship between pH and Electrical Conductivity lake water.

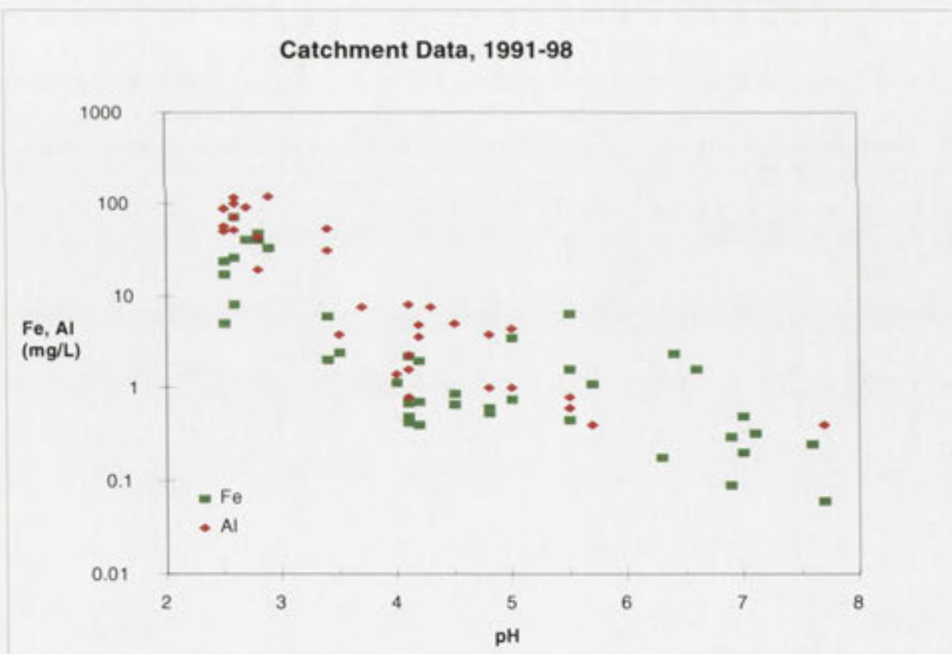


Figure 5.33 Relationship between pH and soluble ions aluminium and iron.

5.6 Discussion and Summary

The Cudgen Catchment supports a range of agricultural and non-agricultural activities and has a long history of different land uses. Dairy farming was the predominant land use activity during the early 1900s with sugar cane production taking over as the primary agricultural activity. Both of these intensive farming activities have resulted in large areas of the lower floodplain being cleared of vegetation and drained of surface water. However, over the last 20 years major changes in land management practices have taken place on the lower catchment with a shift away from cane farming to resort or tourist development, as well as beef cattle farming. Such activities have resulted in the construction of more drains and further acidification problems downstream from the floodplain. Whereas sugar cane was once the dominant land use activity on the lower floodplain there is now mostly unimproved pasture. Sections of the lower catchment degraded to such an extent that there is clear evidence of severe acid scalding. A combination of poor land management and changes in land use has led to major acidification problems requiring urgent attention. It is therefore not surprising that this catchment has been identified as an ASS management priority area in NSW.

Recent soil surveys of the Cudgen Catchment have shown that there is a significant amount of acid stored within the soil profile. More than 500 hectares of the lower catchment has AASS down to a depth of one metre with PASS as deep as 40 metres in some places (White, personal communication, 2001). The total store of acidity within the 500 hectares has been estimated as high as 50 tonne/ha (Tweed Shire Council, 1998). With this vast store of acidity, it has been estimated that it would take over 1000 years before all the acid is leached out of the soil with the potential for further oxidation and acid discharge from unoxidised pyritic soils beyond this time period (White *et al.*, 1997). The application of lime to the subsoil surface is simply not practical nor economical because of the large volumes of lime and the high costs involved in neutralising this large store of acidity. Furthermore, the application of lime at this depth is not only difficult in wet areas (White *et al.*, 1997) but may also result in an increased risk of creating further acidification through the disturbance of partially oxidised and unoxidised sulfidic sediments.

There is no doubt that one of the major impacts on water quality for Cudgen Lake has been the development of the network of drains that cover nearly the entire lower floodplain. It is evident from the hydrological modelling, that the hydrology of the Cudgen floodplain has been dramatically altered by drainage. The impact of such schemes on the relocation of acid surface water from the floodplain to the drainage network, was evident from the modelling results. The drainage network acts as a reservoir for acid waters and a conduit for the efficient transport of acid and acid products to the lake environment. The small tidal exchange that exists between the lake and the ocean is also a significant factor that affects water quality. With such a small tidal exchange there is very little capacity for sea water to effectively neutralise acid from large discharge events. However, the water quality results suggest that although these tidal events are small, they appear to provide an effective neutralisation barrier against acidic waters originating from small surface flow events. Attempts have been made to improve the exchange of sea water through widening the channel between the ocean and the lake. However, this strategy has proven to be unsuccessful resulting in unpredictable tidal conditions and excessive tidal flooding of the lower catchment during large tidal events (WBM Oceanics Australia, 1998). These tidal modifications have not worked, which clearly suggests that future strategies should focus more on treating the source of the problem upstream from the lake, in consultation with land holders and developers.

The down stream impacts to aquatic life and recreational activities from the drainage system is evident from the water quality results. These impacts include large fish kills and the destruction of benthic organisms. The continued acidification of estuarine habitats and, in particular, the frequency of acidification events, often leads to long-term effects such as the depletion of food resources for aquatic life and the disruption to fish reproduction and migration (Sammut *et al.,* 1996). The implementation of land management strategies for combating acidification should be aimed at providing long-term benefits that are economical, rather than providing short-term solutions to what is obviously a long-term problem.

Based on the results presented in this Chapter, there are reasonable grounds to examine the benefits of long-term remediation strategies by using the modelling tools developed here. Clearly, it would be feasible to investigate the effects of a reduced drainage network on the export of acid to the lake environment. The current drainage structure in the Cudgen floodplain would appear to be rather excessive and unplanned with some drains unconnected to the main network. The elimination and re-design of the drainage network should reduce the translocation of acid surface waters from the floodplain to the drainage system. However, there is also a need to examine the impacts that drainage re-design might have on surface water flow and flooding. To assess these impacts and to provide a long-term viable solution to minimising acidification of the lake environment, additional modelling is required.

The hydrological modelling has shown that both rainfall and hence streamflow have high seasonal variability. The monthly streamflow can vary from around 48,000 ML during the summer months when rainfall is high to as low as 5,000 ML during the winter months. The average annual flow was estimated to be around 30,000 ML. This variability not only has an impact on acid concentrations and pH levels in surface flows, but also the mobilisation of acid reserves through the soil profile and its translocation to surface waters.

Since both groundwater and surface water flow are the main factors responsible for changes in the movement and distribution of acid and its products, any changes in the surface water chemistry can provide a good indication of the system dynamics of the catchment. During dry times, the process of evapotranspiration is responsible for controlling the depth of the watertable (White *et al.,* 1993; Lin *et al.*,1995; Wilson, 1995). There is a direct relationship between watertable dynamics, surface water flow, climatic variability and water quality.

The implementation of any remediation strategy or changes to land management practices should consider the characteristics of surface water flow and the watertable dynamics. Land management techniques for controlling surface water runoff have been successfully trialed in the McLeods Creek region of the Tweed (White *et al.*, 1997). These techniques have involved laser levelling of sugar cane paddocks and the removal of drains. Some of these techniques could be used in the Cudgen, to control surface water runoff. However, because all catchments are different, with respect to rainfall and runoff, it is essential to have a good understanding of the current and the possible future changes to climatic processes and land use activities, that will affect watertable dynamics and surface water flow, at the catchment scale. The impact of climate variability on catchment hydrology is a complex issue as it involves factors that are far removed from the events that take place at the catchment scale. These include changes in global weather patterns, such as El Niño and La Niña events. These global weather patterns play an important role in shaping Australian climatic variability (McBride and Nicholls, 1983; Nicholls, 1987; Nicholls, 1988; Nichols and Wong, 1990) and changes in crop responses (Nicholls, 1985). The next chapters will examine in more detail the relationship between climate, surface flows, watertable dynamics and acid outflow events and its impact on aquatic life, including the implications for developing sustainable land management practices for the Cudgen.

CHAPTER 6
Trends in Rainfall Variability in the Tweed

(Photo provided by Mark Tunks)

Chapter 6. Trends in Rainfall Variability in the Tweed

6.1 Introduction

Based on the results shown in the previous chapter and from other studies (Wilson, 1995; Wilson *et al.*, 1999; White *et al.,* 1997) it is clear that climate is the fundamental driver of acidification. As mentioned briefly in Chapter 3, the export of acidic groundwater to surface waters is influenced by two important characteristics of rainfall, firstly the ratio of runoff to precipitation and secondly its variability with respect to time. For the coastal floodplains of eastern Australia, rainfall and hence streamflow, exhibit extreme variability from year to year (White *et al.*, 1997).

Periods of prolonged drought lowers watertable levels and allows for the further oxidation of pyrite and the accumulation of oxidation products within the soil profile. Heavy rainfall following a dry spell results in the mobilisation of these acid reserves to surface waters. Significant changes in water quality of estuaries occur following these events, resulting in mass mortalities of gilled organisms (Brown *et al.,* 1983; Callinan *et al.,*1993; Sammut *et al.*, 1996). An understanding of climate and its variability with respect to time is of fundamental importance for predicting the timing and magnitude of an acid discharge event. This chapter examines the extent of rainfall variability in the Tweed over the last 100 years.

6.2 Analysis of Rainfall Data Using Rainfall Deciles and Percentiles

The determination of climatic drought is closely linked to variability in seasonal rainfall. However, it is difficult to clearly define the severity of a dry spell because unlike other natural disasters there is no precise definition as to what constitutes a drought (Smith *et al.,*1992). For example, a period of low rainfall in one region such as the tropics, might be regarded as high rainfall in another region, where rainfall is generally very low. Factors such as seasonal characteristics should also be taken into consideration.

A good indication of climatic drought can be derived from six or 12 monthly deciles which are solely based on rainfall records for each month of the year. This approach is commonly used by the Australian Bureau of Meteorology to assess drought conditions across Australia and is commonly referred to as the decile method (Gibbs and Maher, 1967). Alternatively, it is possible to use a suitable soil water balance method to measure the extent of climatic drought. Techniques such as the WATBAL method (Keig and McApline, 1974) and the Palmer Index (Palmer, 1965; Alley, 1984) have specific data requirements, other than precipitation, to measure extreme climate variability. These may include solar radiation, wind speed, soil characteristics and evapotranspiration. In Australia, the lack of vital soil and climate data has limited the use of these (otherwise reliable) soil water balance methods.

One advantage in using rainfall deciles to assess the severity of a dry spell is its simplicity and lack of reliance on water balance equations. The Palmer Index is calculated directly from monthly moisture anomalies and requires a detailed water balance calculation. Smith *et al.* (1992) showed a strong correlation between the Palmer Index and six monthly rainfall deciles, which suggested that a normalised index of available moisture can be calculated just as effectively using six-monthly rainfall totals. The rainfall decile for a particular month of the year, is defined by ranking all the rainfall recorded for a specified period, against the total for the same period. The first decile, or 10 percentile, is the amount of rainfall which does not exceed 10 percent of all totals. This is identified as a period of significant below average rainfall. Similarly, the fifth or median is the rainfall amount that is not exceeded in 50 percent of the total.

By using the method proposed by Smith *et al.*(1992), six monthly and twelve monthly deciles were calculated using long-term rainfall records from two stations, namely Murwillumbah and Tweed Heads, for the period 1924 to 2000. These two stations were chosen for two reasons. The first was to examine climatic drought variability between coastal and inland regions of the Tweed Catchment and secondly, the rainfall data obtained from both stations were continuous and long-term. Six and twelve monthly deciles were calculated for each month using the preceding six or twelve months of rainfall including the nominated month. For example, the three monthly decile for January, is the total rainfall for January, February and March. Likewise, the three monthly decile for February is the total rainfall for February, March and April. The totals for each month were ranked in ascending order from lowest to highest rainfall, to produce a monthly sequence of rainfall percentiles. The 6 and 12 monthly percentiles for Murwillumbah data are shown in Figures 6.1 and 6.2 respectively. These percentile rankings are compared against monthly percentiles.

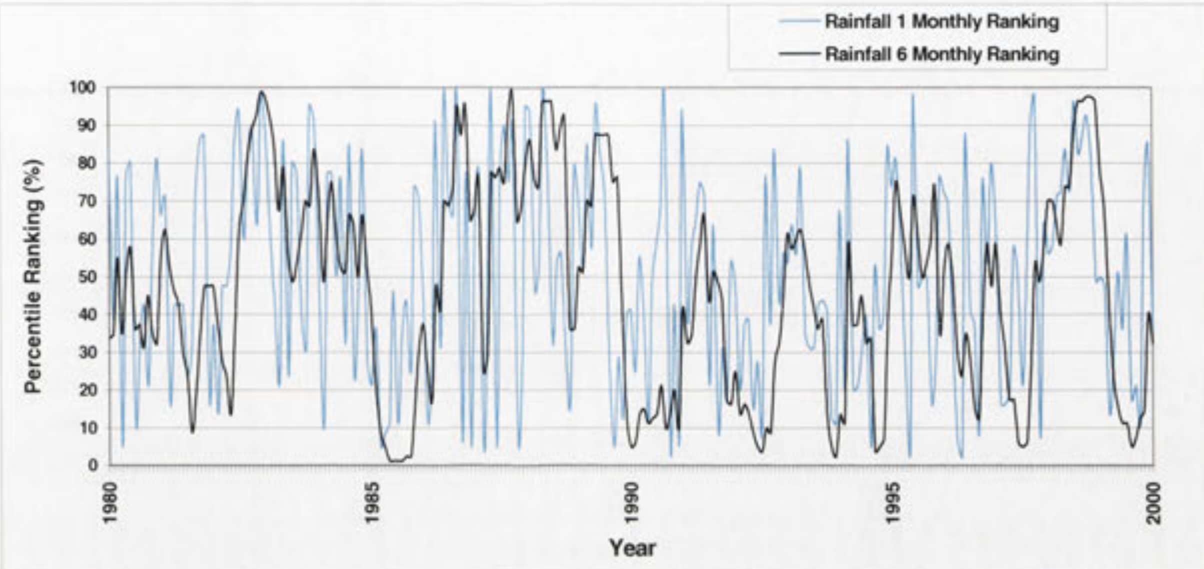


Figure 6.1 Percentile ranking of rainfall for one month of data plotted against 6 Monthly Rainfall data for Murwillumbah.

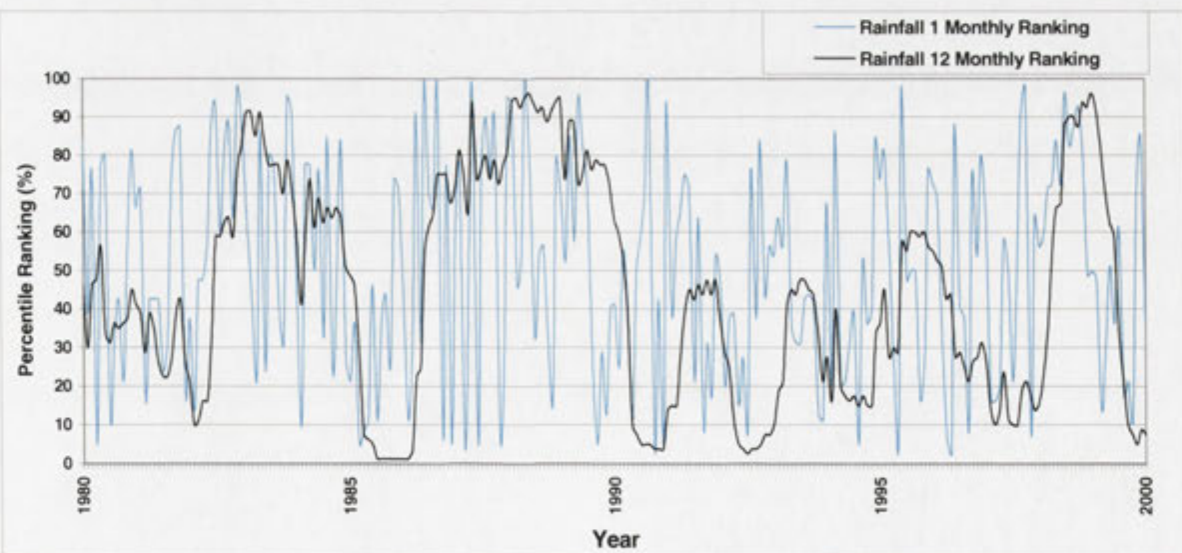


Figure 6.2 Percentile ranking of rainfall for one month of data plotted against 12 Monthly Rainfall data for Murwillumbah.

These graphs clearly show that the monthly data is very noisy, with extreme variation in rainfall on a month to month basis.

The 6 and 12 monthly deciles for Tweed Heads and Murwillumbah for the years 1984 to 2000 are shown in Figures 6.3 (a-b) and 6.4 (a-b) respectively. Similarly, as with the percentile rankings shown in Figures 6.1 and 6.2, the increased smoothing imposed by the 12 monthly deciles with respect to the 6 monthly deciles is apparent. The 12 monthly deciles provide a more transparent picture of the duration and severity of the dry periods. Judging from the these results it would appear that the 1986 drought was the worst on record for this time period, with rainfall deciles well below 10 percent extreme dry for the entire 1986 calendar year. The duration of the dry spell for most years except 1986 was more pronounced for Murwillumbah than for the Tweed, indicating that the coastal region received slightly higher rainfall during these extremely dry periods.

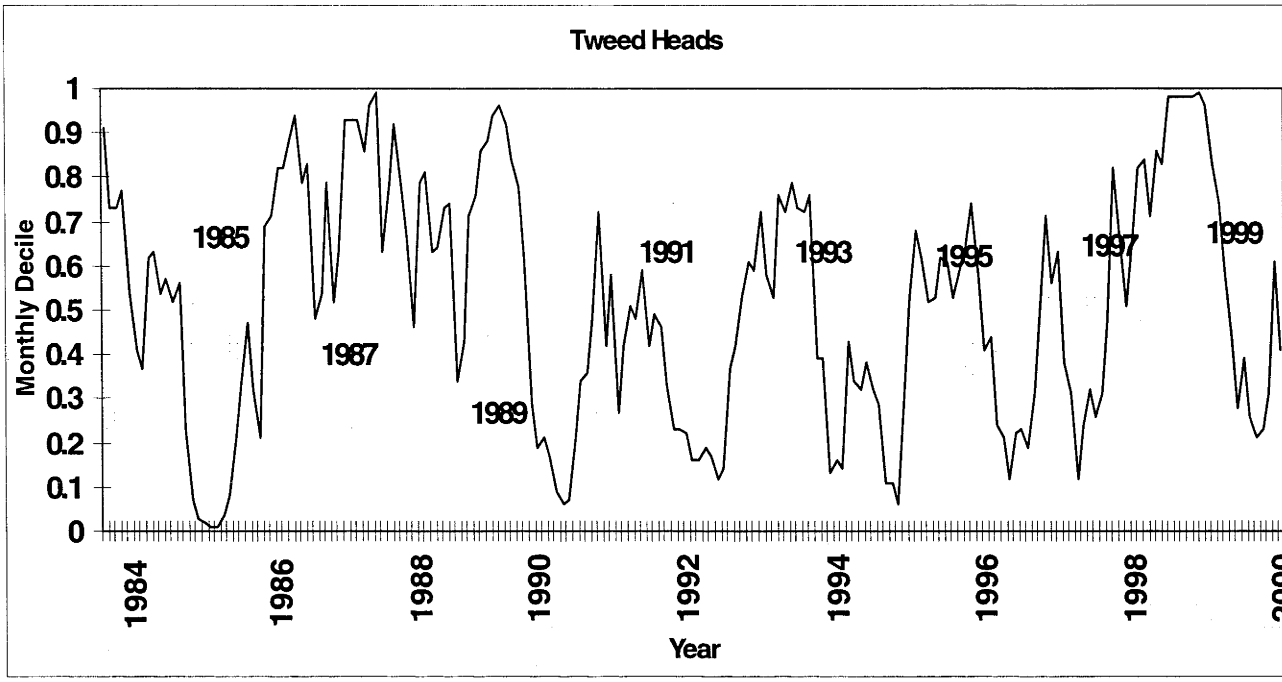


Figure 6.3(a) 6 Monthly Rainfall Decile for Tweed Heads from 1984 to 2000.

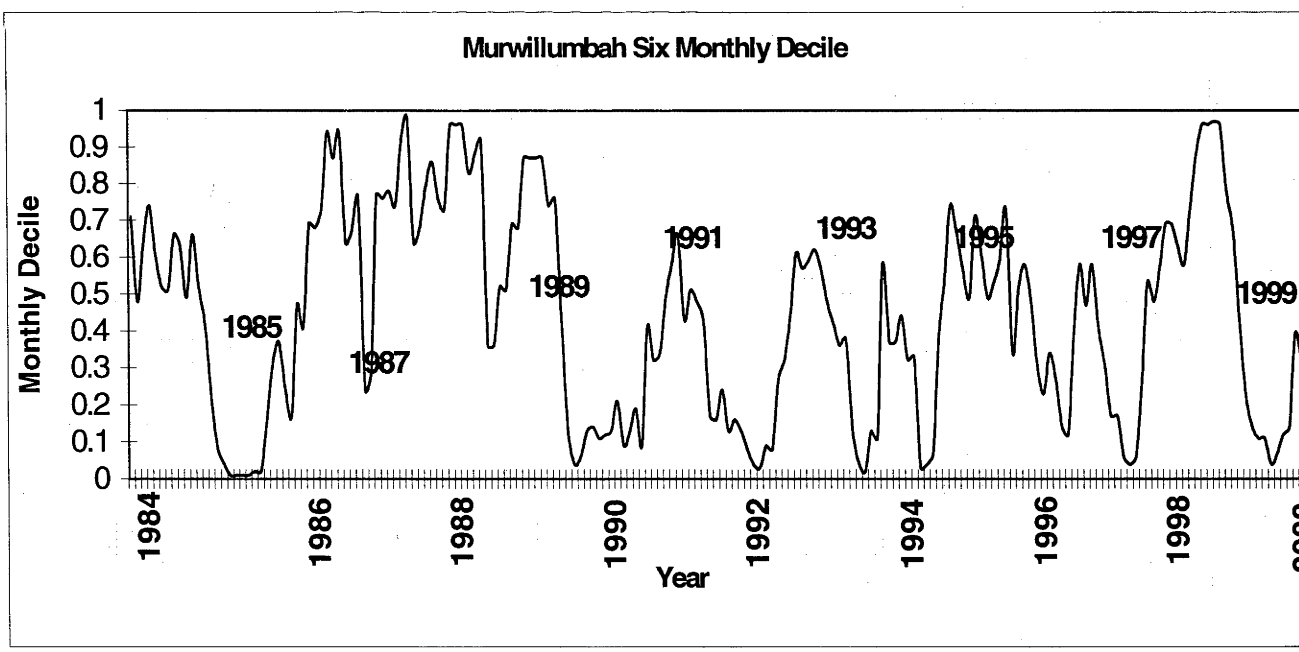


Figure 6.3 (b) 6 Monthly Rainfall Decile for Murwillumbah from 1984 to 2000.

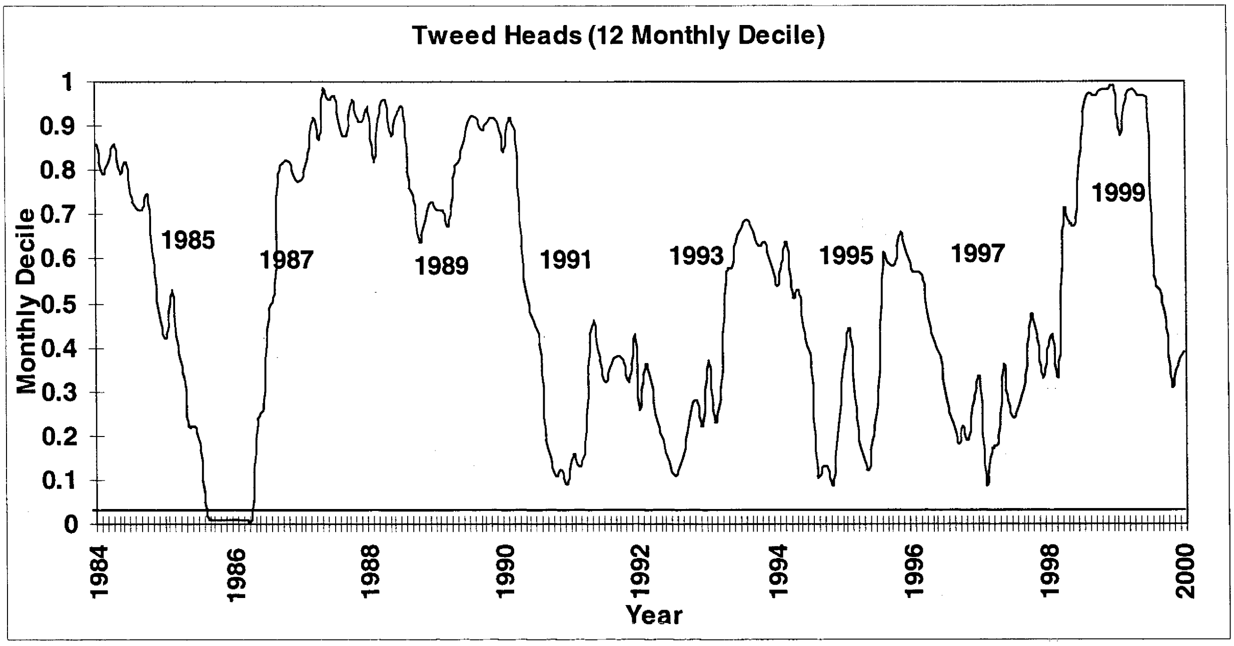


Figure 6.4 (a) 12 Monthly Decile for Tweed Heads from 1984 to 2000.

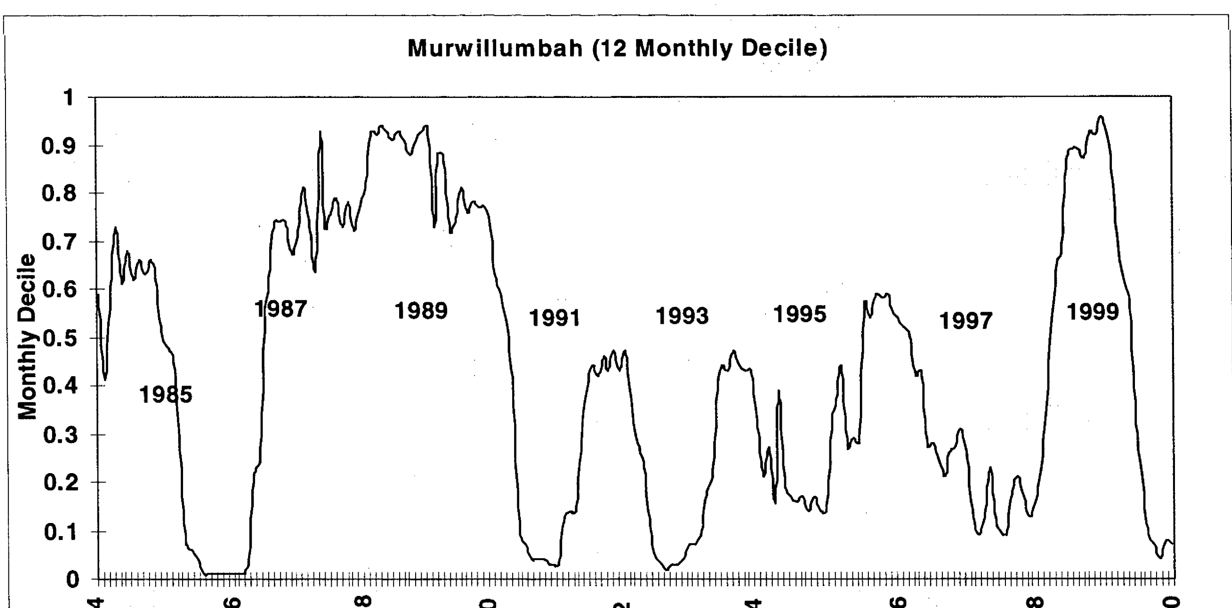


Figure 6.4 (b) 12 Monthly Decile for Murwillumbah from 1984 to 2000.

6.3 Relationship with the Southern Oscillation Phenomenon

The localised climatic patterns of severe dry and wet revealed in section 6.2 is greatly influenced by a much larger climatic phenomenon. The interannual variations in the rainfall pattern from year to year are due to changes in the strength of the Walker Circulation System (Walker, 1924) also known as the Southern Oscillation (SO). The Walker Circulation System is an east-west atmospheric circulation phenomenon characterised by the circulation of air between Indonesia and the eastern Pacific region.

The strength of the SO is determined by measuring the difference in air pressure between the Indonesian-Australian region and the central region of the Pacific Ocean at Tahiti (Drosdowsky and Williams, 1991). Another method which can be used to measure the phase and intensity of the SO is Sea Surface Temperature (SST) (Rasmusson and Carpenter, 1982). However, the normalised (to a standard deviation of 10) difference in pressure between Tahiti and Darwin is the most commonly used method and is generally referred to as the Southern Oscillation Index (SOI) (Troup, 1965). The SOI is defined as:

$$SOI = 10.\frac{\Delta p - \mu_{\Delta p}}{\sigma_{\Delta p}} \tag{6.1}$$

Where Δp is the difference in monthly sea level pressure difference between Tahiti and Darwin, while $\mu_{\Delta p}$ represent the long-term mean and $\sigma_{\Delta p}$ is the standard deviation for the month in question.

An increase in pressure, is often associated with an increase in warming at the ocean surface, which results in a corresponding increase in SST and convective rainfall. A positive SOI value is indicative of stronger Pacific trade winds and higher sea temperatures in the northern regions over Australia. This event is referred to as a La Niña event. A negative SOI value on the other hand results in an increased warming of the central and eastern Pacific Ocean near South America and a weakening of the Pacific trade winds. This type of event is referred to as an El Niño event. The correlation between the SOI and the oceanographic El Niño phenomenon was first described by Bjerknes (1966).

Ropelewski and Halpert (1987) had identified global and regional scale precipitation patterns closely linked to the El Niño-Southern Oscillation (ENSO) cycles. There have also been a few studies which have shown that ENSO cycles have a strong influence on Australian rainfall (McBride and Nicholls, 1983; Nicholls, 1988). For eastern Australia, an El Niño event or a negative SOI value is associated with an increased probability that climatic conditions will be much drier than normal (Nicholls, 1988). The studies conducted by Nicholls (1988) concluded that "areas affected by ENSO are truly lands of drought and flooding rains".

El Niño events generally occur on a time scale of 2-8 years and persist for periods of between 6 to 18 months (Mantua, 2002). The Commonwealth Bureau of Meteorology (http://www.bom.gov.au/climate/enso/australia_detail.shtml) provides a comprehensive record of El Niño events and their impact on Australia's climate since 1902. This web site also provides time lapse decile map loops for all El Niño event periods. Figure 6.5 shows the monthly SOI and the frequency of El Niño and La Niña events for the period 1947 to 2000. From 1945 to 2000 there were three events (1953, 1980-82 and 1996-97) which recorded a strong negative SOI. Between 1982 and 2000 there were six El Niño events with SOI reading less than –10. These events are summarised in Table 6.1

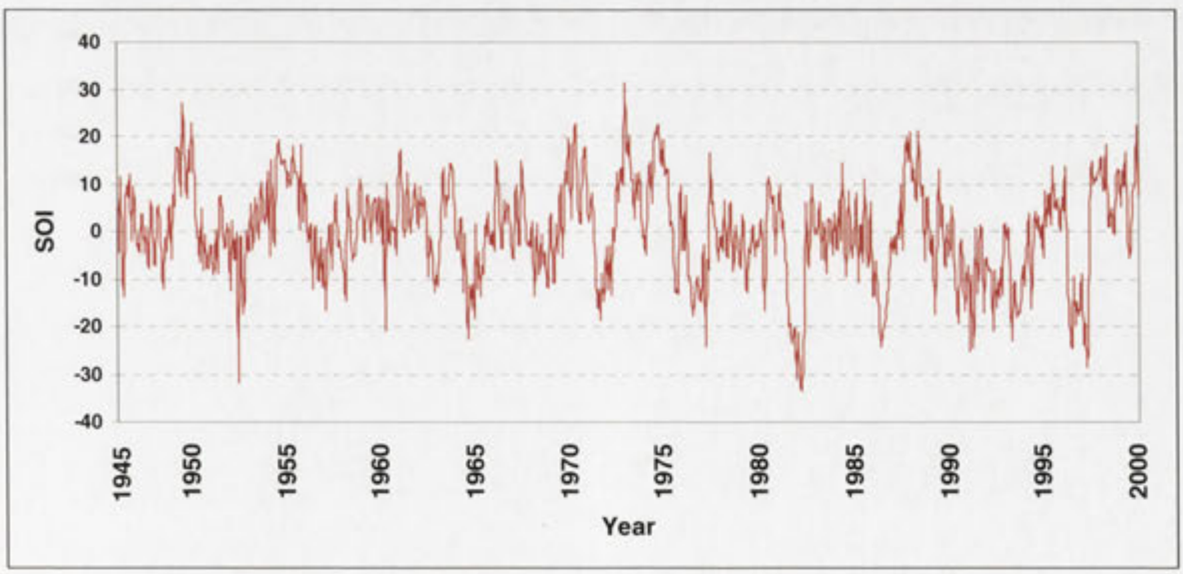


Figure 6.5 The monthly Southern Oscillation Index for the period 1945 to 2000.
(Source: Bureau of Meteorology (2003a).

Table 6.1 Summary of El Niño Events and the relative strengths of SOI and SST for each El Niño event.

Year(s) in which an El Niño Event Took Place	Strength (SOI and Sea Surface Temperature SST)
1982-83	**SOI –Very Strong** **SST- Very Strong**
19987-88	**SOI-Moderate to Strong** **SST- Moderate to Strong**
1991-92	**SOI-Moderate to Strong** **SST-Moderate to Strong**
1993-94	**SOI-Moderate** **SST- Weak**
1994-95	**SOI-Strong** **SST-Weak to Moderate**
1997-98	**SOI-Strong** **SST-Very Strong**

(Source: The Commonwealth Bureau of Meteorology (http://www.bom.gov.au/climate/enso/australia_detail.shtml)).

The years 1997-98 recorded a strong SOI and a very strong SST. The eastern sector of the continent experienced either below average rainfall or lowest on record from April 1997 to March 1998. However, despite the strong SOI and SST readings for this period, the overall impact from this particular event was classed as weak because of good, widespread rainfall during April, May and September, providing crops with much needed relief from the very dry summer months. According to the Bureau of Meteorology, the rainfall decile records for April 1998 showed rainfall decile readings ranging from “average” to “highest on record” for the most of Australia. The 1994-95 El Niño event also affected most of Australia including the Northern Territory and Western Australia. From March to December, rainfall was in the lowest 10% of totals. For eastern Australia, above average rainfall occurred during November and December. The year 1993 also recorded a moderate SOI with an El Niño cycle lasting from March 1993 to April 1994 (13 months). According to the Bureau of Meteorology records, the 1991-92 El Niño event affected around three quarters of Queensland with this state recording decile one for 9 months from March 1991 to November 1991. The northern half of NSW was also seriously affected, however, this region had experienced good rainfall during May 1991 with above average rainfall recorded at Tweed Heads for this month. September 1991 was very dry, August 1991 was the driest on record. The 1987-88 El Niño event was similar to the 1991-92 event because for some months during the El Niño phase (i.e., March 457mm and May 505mm) there was above average rainfall. Interestingly, conditions in the Tweed were very dry before the 1991-92 and 1987-88 El Niño events had officially been declared. The historical rainfall records for Murwillumbah and Tweed Heads are shown in Appendix B.

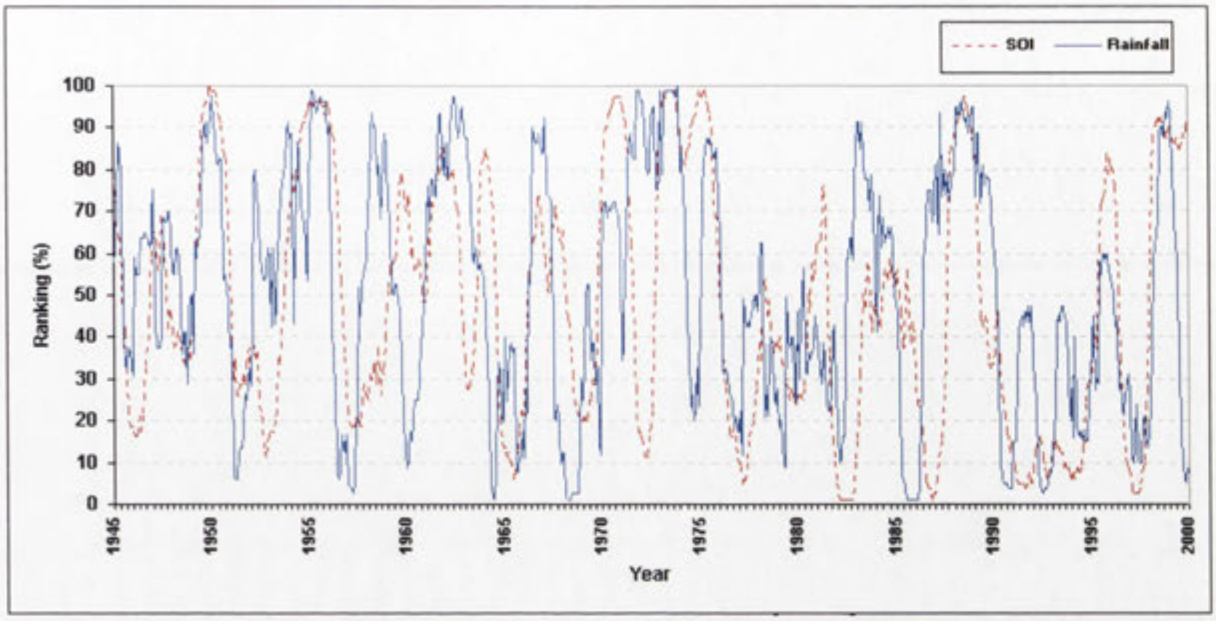
6.3.1 Relationship Between Rainfall and SOI for the Tweed.

To determine how the relationship exists between rainfall and ENSO for the Tweed, a series of correlation coefficients were calculated for SOI and accumulated monthly rainfall, over selected time periods. This involved totalling the monthly rainfall for 6, 12, 24, 36, 48, 72, 84, 108 and 144 months up to and including the month in question. This effectively decreases the coefficient of variation and smooths any variation in the data as the totalling process is increased. Totals were then ranked as a percentage using the "percentrank" function in EXCEL. Table 6.2 lists the correlations between ranked accumulated rainfall and SOI for selected months. Figures 6.6 and 6.7 show the relationship between the SOI and the percentile ranking for 12, 24, 72 and 108 month periods.

Table 6.2 Correlations between ranked accumulated rainfall and SOI for selected months.

Time Period	Correlation Coefficient
6	0.2384
12	0.4145
24	0.5601
36	0.6251
48	0.6802
72	0.7195
84	0.7218
108	0.6273
144	0.5463

(a)



(b)

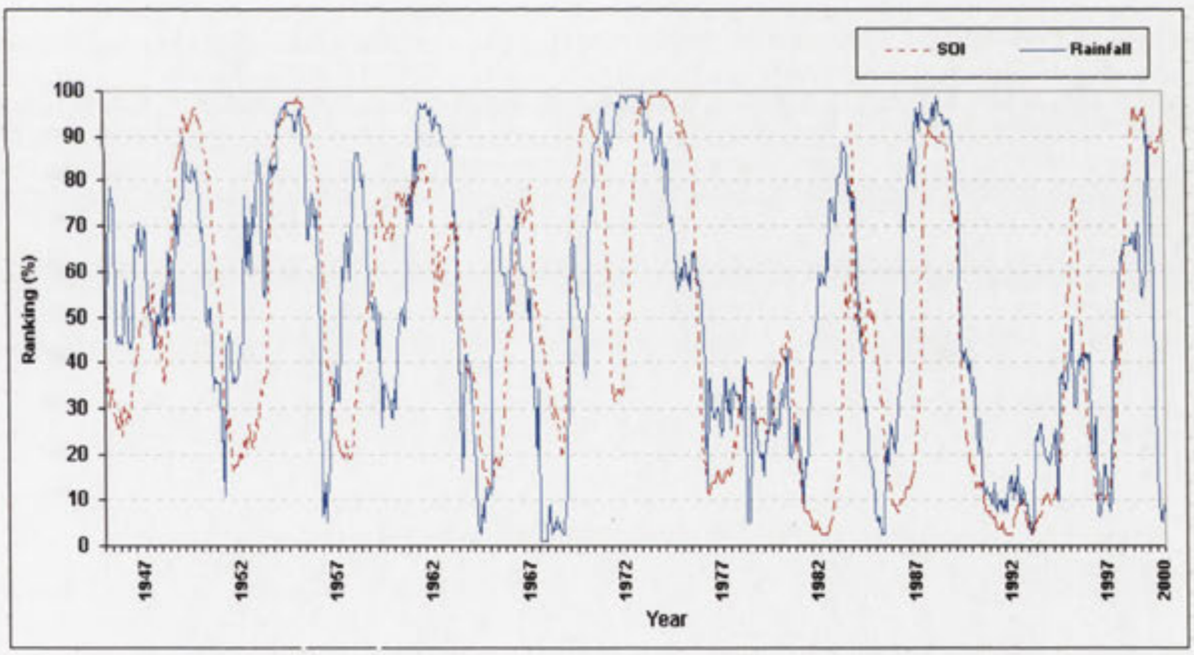
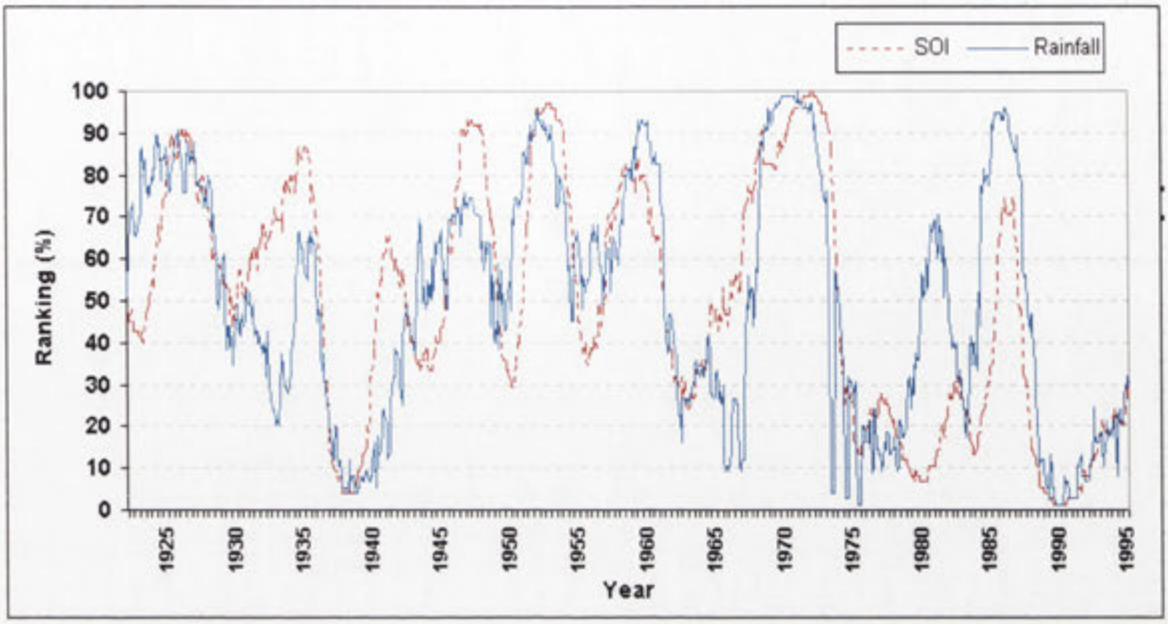


Figure 6.6 Comparison of percentile rankings for Murwillumbah rainfall and SOI for (a) 12 and (b) 24 month accumulation periods.

(a)



(b)

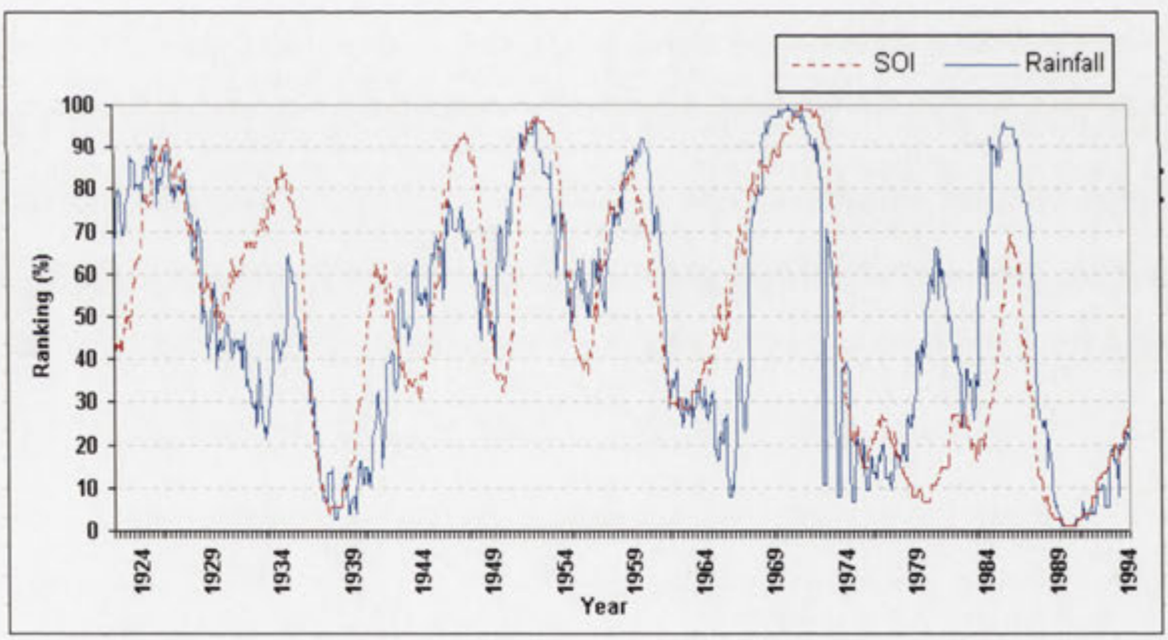


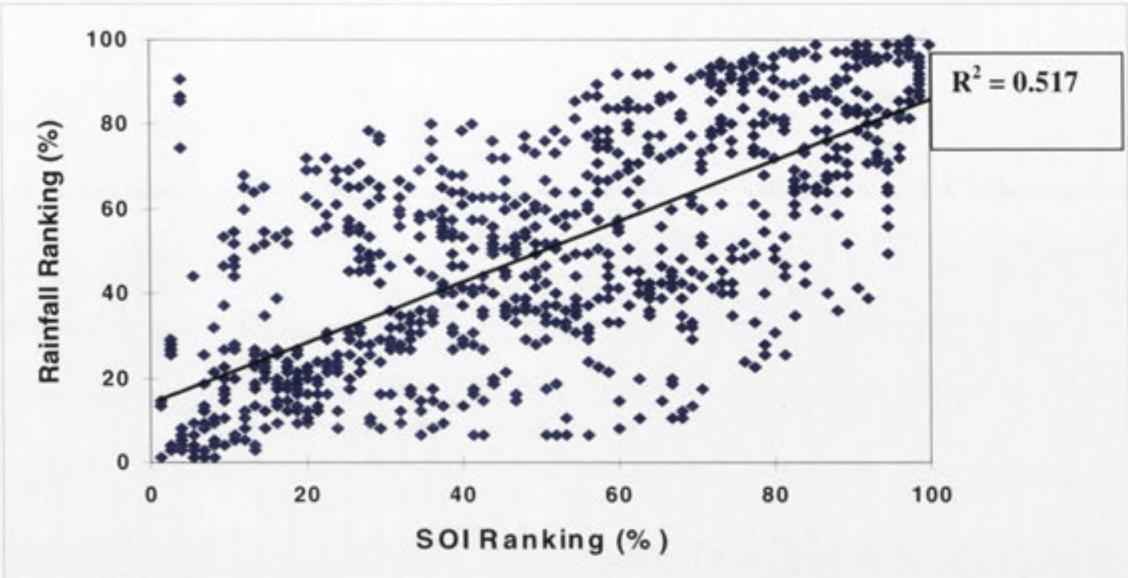
Figure 6.7 Comparison of Percentile rankings for Murwillumbah rainfall and SOI for (a) 72 months and (b) 84 month accumulation periods.

These results indicate a good correlation between SOI and rainfall for the Tweed Catchment over periods greater than 84 months. It can be seen from Table 6.2 that the correlation between SOI and rainfall increases as the data are progressively smoothed. The correlation increases from 0.2384 for 6 months of smoothing to 0.7218 for 84 months of smoothing. The best correlation is between 72 and 84 months (or 6 to 7 years) which is not surprising considering El Niño events occur at intervals from 3 to 8 years. The correlation coefficient decreases as the data is progressively smoothed for time periods greater than 84 months. For the 72 and 84 month data, around 52 % (R^2 =0.517, R^2= 0.521) of the variance can be attributed directly to the SOI (see Figure 6.8 a and b), which indicates that the ability to predict an El Niño event or La Niña event on a six year cycle is around 50 percent. The correlation coefficient squared (R^2) for the entire Australian continent is around 0.25 (Nicholls *et al.*, 1997).

The correlation between SOI and rainfall has also been studied for other regions by using the decile method. For example, White *et al.,* 1999b looked at the relationship between negative values of SOI and rainfall for South Tarawa, Kiribati, in the Central Pacific. They derived a series of correlation coefficients by ranking the negative SOI and ranked accumulated rainfall over similar time periods (Figure 6.9). Their work showed a strong correlation between negative SOI and rainfall with 67% (R^2 = 0.66) of the variance attributable to the SOI, for 12 months of accumulated rainfall. Clearly, this result is quite different from the results obtained for Murwillumbah which showed there was less correlation between SOI and accumulated rainfall for similar time periods. This difference in the correlation is attributed to a difference in the geographical location of these two sites, with respect to the relative timing of ENSO cycles.

The methodology used here has assumed that both SOI and rainfall are in phase. An examination of Figures 6.6 to 6.7 shows that in some cases there is a lag between the SOI and the rainfall with the SOI either leading the rainfall for a period of two to three months or following the rainfall for similar time periods. Nicholls *et al.* (1996) work showed a similar year to year variation between the SOI and rainfall for averaged annual rainfall across Australia.

(a)



(b)

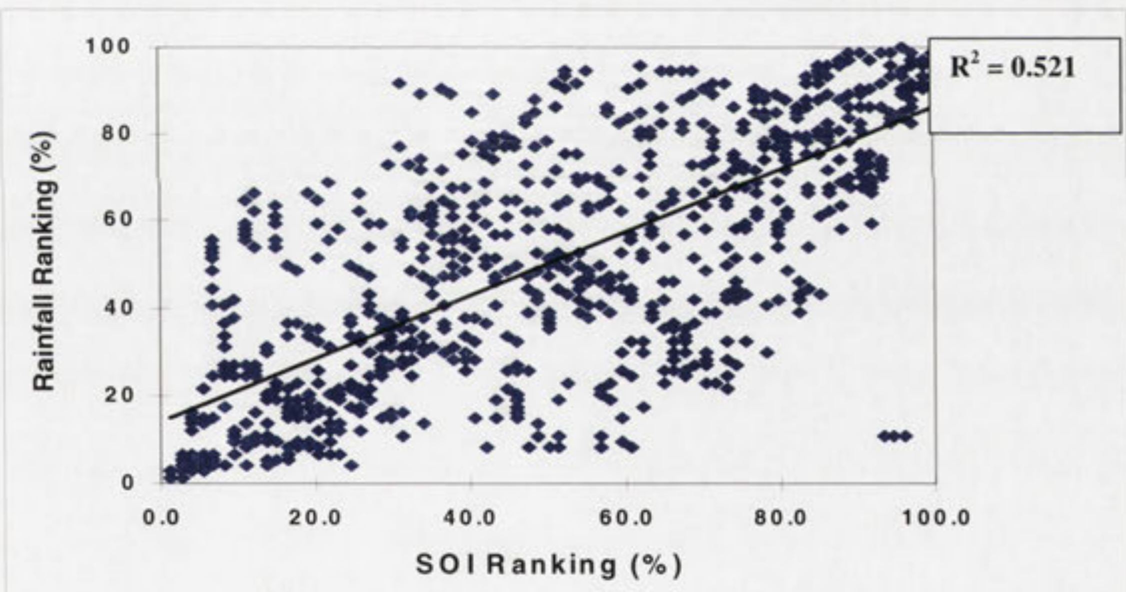


Figure 6.8 Correlation between rainfall percentile ranking and SOI percentile ranking for (a) 72 and (b) 84 month accumulation periods. The correlation coefficient squared (R^2) is around 0.52 for both accumulation periods.

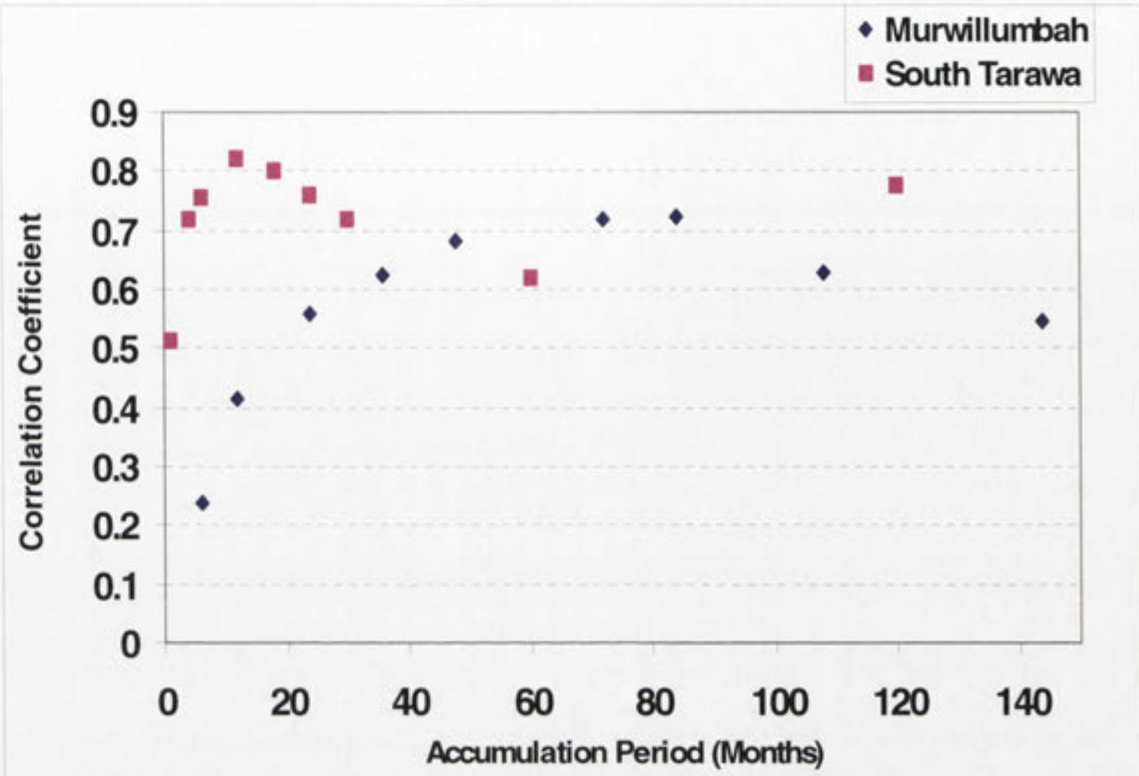


Figure 6.9 Comparison of correlation coefficients between Murwillumbah and South Tarawa, Kiribati (Adapted from: White et al., 1999b).

6.4 Trends in Rainfall

Computer models have been used extensively to predict changes and trends in climate. The new generation of complex global climate models (GCM), examines climate change in response to changes in atmospheric chemistry through enhanced greenhouse gas production. An analysis of combined global land and marine surface temperature records since 1850 show a dramatic rise in surface temperatures since the late nineteenth century (Jones *et al.*, 1999). This rise in temperature has been attributed to a build up of greenhouse gases resulting from human activities (Burroughs, 1997). However, it is not certain whether global warming can be explained in terms of human activities or whether it is part of the natural climatic cycle. Based on geological records, there has been an appreciable variation in the climate over the last 1000 million years in which there were a series of changes from glacial to interglacial periods occurring every 100,000 years (Bryant, 1997). These variations coincided with changes in the rotation of the earth's orbit known as Milankovitch cycles (Milankovitch, 1941). Such changes affect both the distribution and quantity of solar radiation which reaches the earth.

According to Jones and Pittock (1997), climate variability can be divided into five categories:

(1) spatial or regional variability as previously displayed in the spatial rainfall maps;
(2) multi-decadal variability, in which climate changes have taken place over a period of decades;
(3) inter-annual variability, where there are climatic changes taking place on year by year basis; the ENSO cycles experienced in Australia are the major cause of inter-annual variability.
(4) intra-seasonal and seasonal variability, which describe the relationship between seasons including changes within seasons;
(5) daily variability which describes changes in temperature and rainfall patterns on a daily basis.

The ability to identify changes in climate patterns beyond the short-term diurnal and seasonal variations is an essential element in determining if longer term changes in the climate are occurring. The seasonal cycle and how it varies over time is regarded as the most reliable pattern of climate change.

6.4.1 The Seasonal Trend Decomposition using Loess (STL) Procedure

The best way to view changes in the seasonal cycle is to analyse variations from month to month for the term of the series. The Seasonal and Trend decomposition using Loess (STL) is a graphics based statistical procedure developed for the analysis of time series data (Cleveland and Devlin, 1988; Cleveland *et al.*, 1988; Cleveland *et al.*, 1990). STL, which is implemented in S-Plus (Becker *et al.,* 1988), is an iterative non-parametric smoothing method that uses an algorithm to determine the trend and seasonal components by progressive filtering of the data using Loess (short for local regression). Similar to splines, Loess uses a regression techniques to determine an estimate of an unknown value from an independent X_i and a dependent variable Y_i where i = 1 to n indices of the observed data. The loess regression curve:

$$Y_i = g(x_i) + E_i \qquad 6.2$$

Where E_i is a random error used to smooth Y_i as a function of any number of independent variables. Loess uses a weighted smoothing parameter to fit a polynomial to a set of variables (X_i, Y_i) so that an accurate picture of the signal can be generated. The weighted parameter works by assigning a greater weight to X_i when X_i is close to X with the weights decreasing as X_i increases in distance from X. The mathematical description of STL is reviewed by Cleveland *et al.*,(1990).

The smoothing function and their respective bandwidths define the trend and seasonal component. The STL procedure applies to time series and can be defined as:

$$Y_t = T_t + S_t + R_t \qquad 6.3$$

Where Y_t is data for a time series measured at n times $t = 1,\ldots..,n$,

T_t is defined as the "Trend" component, S_t the "Seasonal" component and R_t defined as the "Residues" or the remainder.

6.4.2 Long and Short-Term Generalisation of Rainfall Data Using Loess

The aim of this section is to identify rainfall patterns with different frequency of occurrence as well as its duration over a particular time period. To achieve this STL was used to "decompose or generalise" to data into "Trend", "Seasonal" and "Residual" components by a process of progressive filtering of the rainfall data using Loess for different time periods (Cleveland and Devlin, 1988; Cleveland *et al.*, 1988; Cleveland *et al.*, 1990; Cleveland and Grosse, 1990) (Figure 6.10). This process is defined as the components (i.e., Trend, Seasonal and Residual) of the time series. Examples of the different smoothing time periods are provided in Table 6.3. STL identifies the seasonal component prior to progressive filtering to reveal the trend and residual components.

Since the rainfall records used in this study stretch over a long period (80-100years), the STL procedure allows for generalisation of the data, by progressive smoothing, to identify long, medium and short-term (e.g., decadal) and seasonal components. The STL procedure implemented in S-Plus was used to define the components of the time series for Tweed Heads and Murwillumbah rainfall.

Table 6.3 Common smoothing parameters for STL analysis and their respective time periods.

Smoothing Parameter	Examples
Very long	60 years
Long	30 –40 years
Medium	16 years
Short	8 years
Seasonal	12 monthly

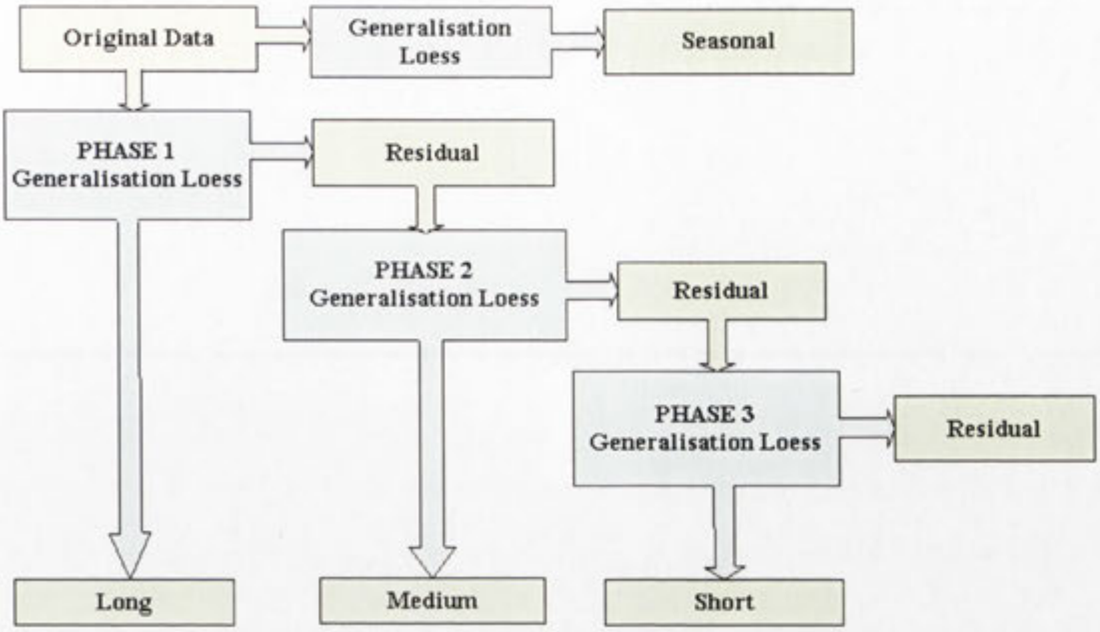


Figure 6.10 Rainfall data is progressively filtered to identify time series components. The seasonal component is removed prior to filtering.

Figures 6.11 and 6.12 shows the "Trend" component using the three smoothing parameters (i.e., long, medium and short), the "Seasonal" component and "Residuals" for Tweed Heads and Murwillumbah rainfall respectively.

The graphs are organised into 6 key components in the following order:

- the raw data
- the long, medium and short-term smoothing components
- seasonal component
- residual component

When interpreting the results it important to look for the following:

- the time period between the peaks and troughs and their average
- the number of repetition of peaks and their duration
- different periodicities and time patterns

An examination of the "Trend" component clearly shows that the different time series (long, medium and short) produces varying amplitude of the components or smoothing of the data. The long-term smoothing produces a low amplitude, low frequency signal. A comparison of all three time series components reveals that the amplitude increases with shorter time periods. The long-term component for Tweed Heads (Figure 6.11) reveals no distinguishable pattern, whereas, the long-term component for the Murwillumbah rainfall reveals a more cyclic pattern prior to 1960 with a 20 year time period spanning each peak. The medium term component for Murwillumbah rainfall revealed that before 1920 and after 1970 there was a fairly consistent and distinguishable 10 year cycle of dry and wet. It is interesting to note the irregular pattern between these two time periods (Figure 6.12). The short-term components show a more distinguishable and consistent pattern of wet and dry than the medium and long-term components. The average time span across and between peaks generated by the short-term smoother is around 6 to 7 years. Tweed Heads rainfall also shows an irregular non-cyclic pattern prior to 1950 for the short and medium term components but exhibits a strong cyclic pattern after 1950 particularly for the short-term component (Figure 6.11). This cyclic pattern in the short-term component shows signs of weakening from 1990 onwards, thus returning to a more irregular, non-cyclic pattern.

The "Seasonal" component revealed a strong rainfall seasonality component around the late 1950s. This high rainfall seasonal trend reaches its peak during 1950 but gradually weakens. We are able to see this much more clearly in the Murwillumbah data. It is also apparent from these results that there was a strong rainfall seasonality component post-1900 (Figure 6.12). Without longer term rainfall records, it is not possible to accurately determine if this 50 cycle will continue to follow the same pattern in the future. If so, we would probably expect a continuation of low rainfall seasonality for the next decade or so before there is a return to a period of higher seasonal rainfall.

These results clearly show that rainfall variability between 1880 to 2000, for the Tweed Catchment, displayed periods that were regular (i.e., cyclic pattern of wet and dry) or highly irregular (i.e., no distinguishable cyclic pattern). Unfortunately, there is no explanation for the inconsistency displayed in these results.

Figure 6.11 Time series, season and residual components for Tweed Heads rainfall from 1920-2000. Values are expressed in mm.

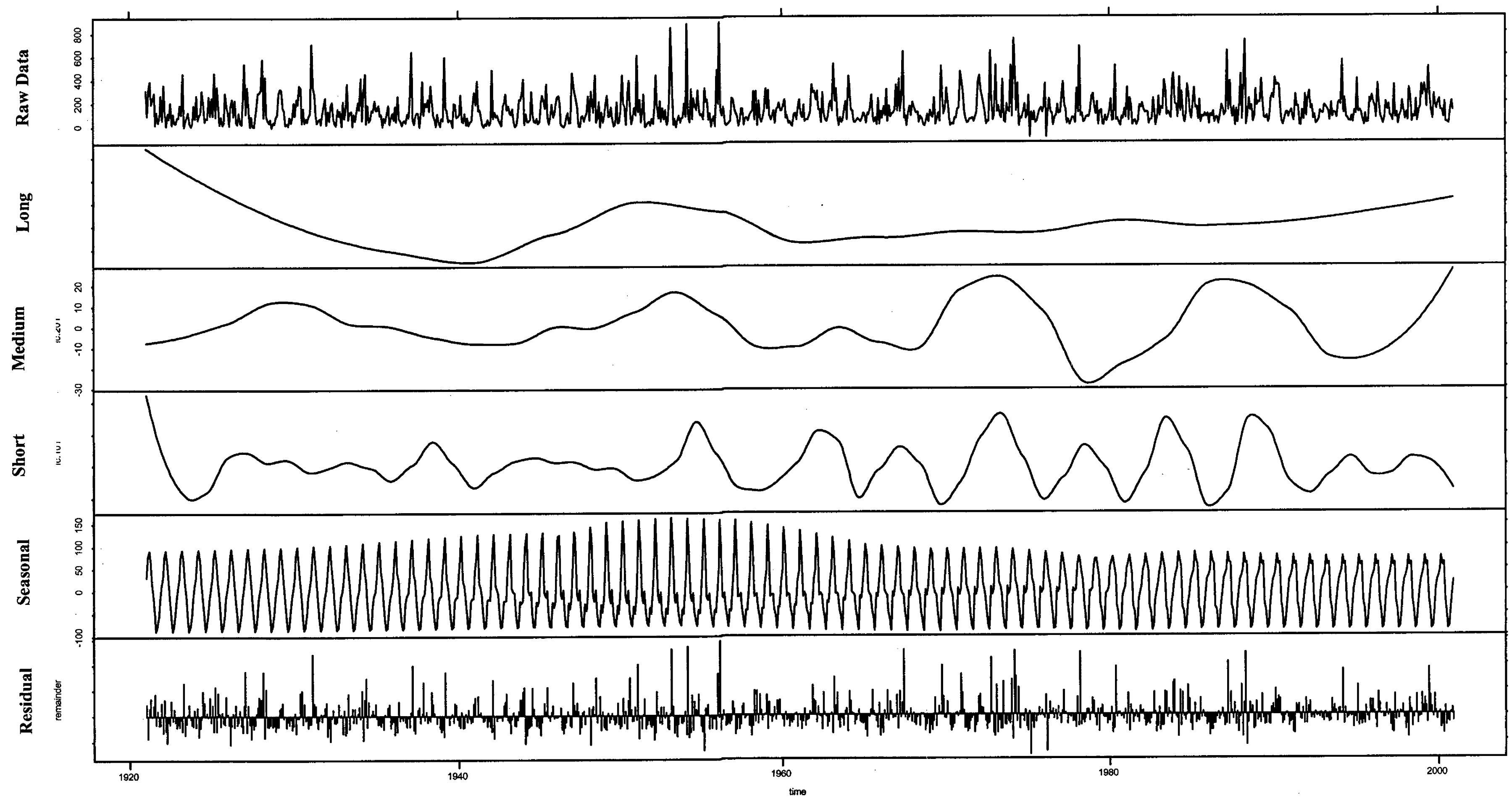
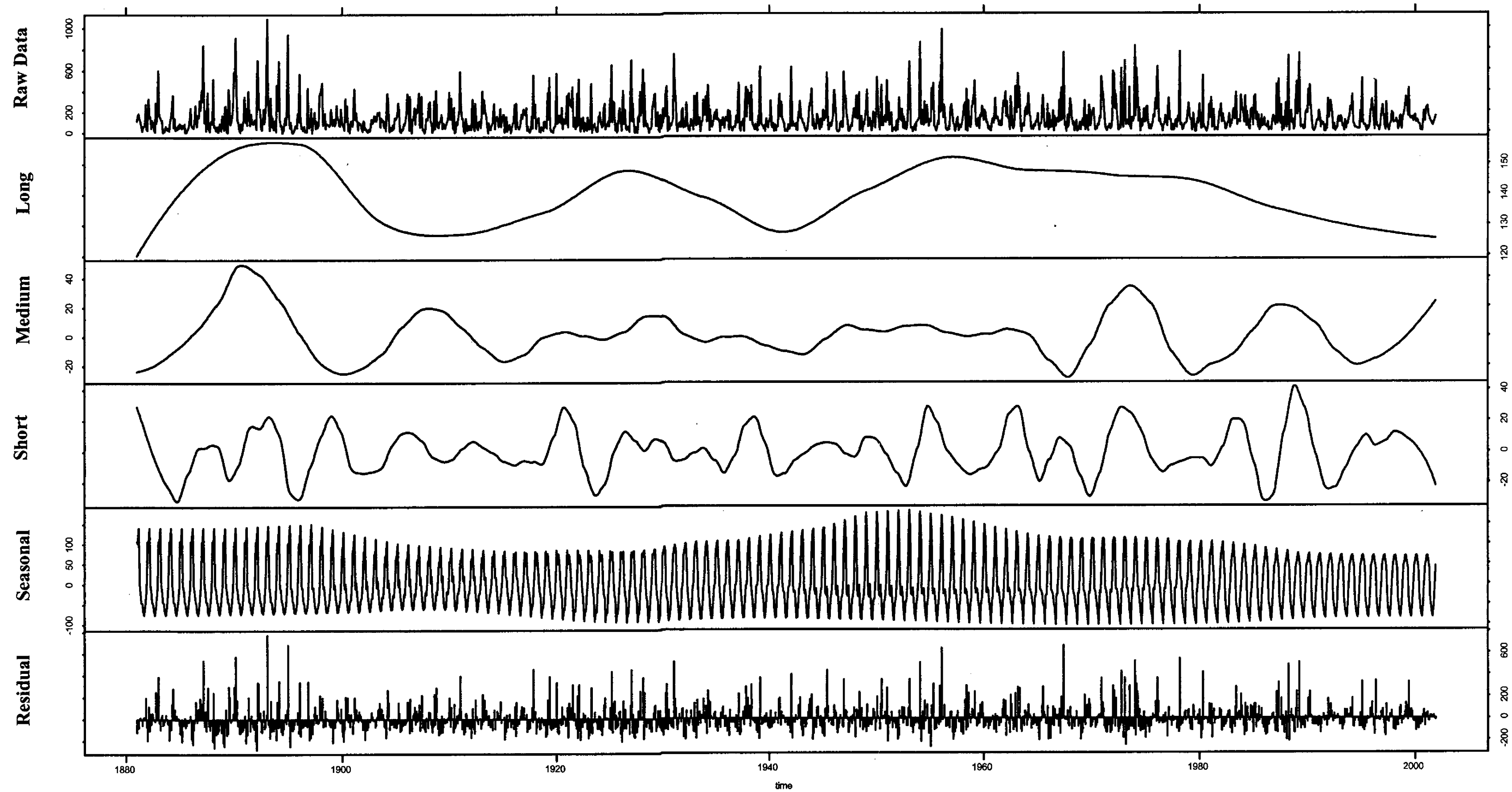


Figure 6.12 Time series, season and residual components for Murwillumbah rainfall from 1880-2000. Values are expressed in mm.



6.4.3 Determination of Seasonality using the Cycleplot Method

The seasonal component can also be subjected to varying degrees of smoothing through Loess. The output generated from this process, referred to as the cycleplot, is a monthly profile that defines a shift in the monthly seasonal series (Cleveland *et al.,*1990). The monthly profile is graphically displayed as a series of horizontal lines that represent mid-mean line (See Figure 6.13). With this technique, the idea is to look for marked changes in the peaks and troughs around the mid-mean line, for each month, which indicates whether the monthly rainfall has deviated from the mid-mean over time. Figure 6.13 provides an example of the types of variation that can be encountered in the cycleplot.

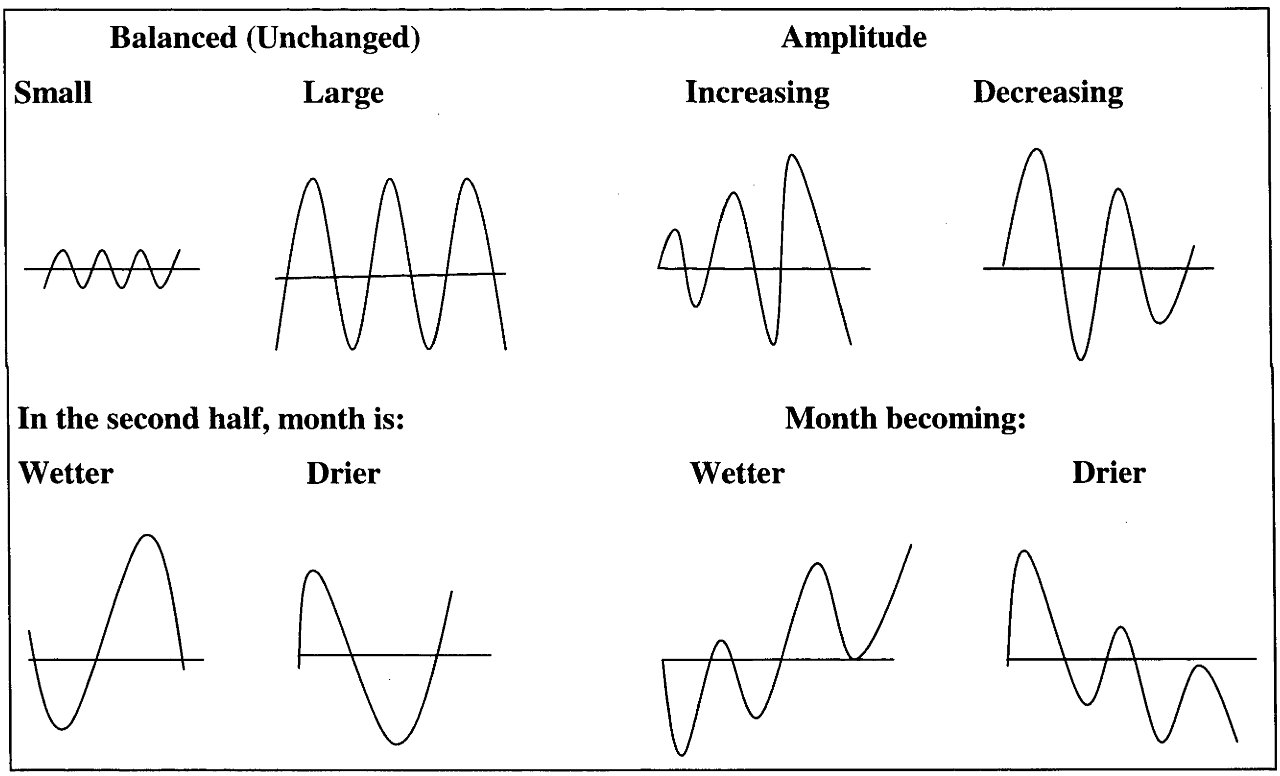


Figure 6.13 Typical patterns of variation in the monthly cycleplot.

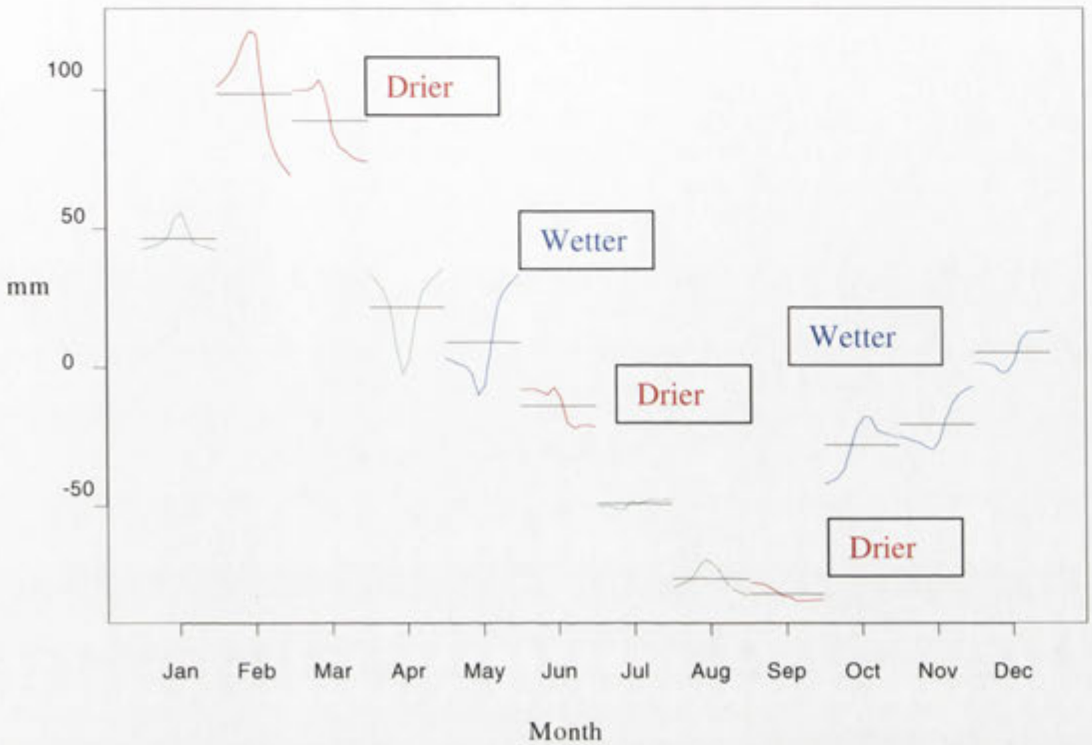
The seasonal rainfall component for Tweed Heads from 1920 to 2000 using cycleplots with long (31 years) and very long (61year) term smoothing is shown in Figure 6.14. If we look for shifts in the seasonal rainfall we find:

- there is a marked change in seasonal rainfall component with conditions becoming notably drier for February, March, June and September. These changes were the same for both short and long-term smoothing.
- the months with the strongest signal for becoming drier were February and March.
- a shift towards higher rainfall was evident for May, October, November and December with the strongest signal for May.
- there was no change in the seasonal rainfall component for January, April, July and August.

The monthly seasonal component for Murwillumbah (Figure 6.15) revealed similar results except for July and August. From these results it is apparent that for Murwillumbah the July rainfall has become drier, whereas August showed a trend towards slightly higher rainfall.

It is interesting to note that the shift towards drier conditions for February, March, June, and September and an increase in rainfall for May, October and December was also reflected in the LAPGRD analysis of the short-term spatial rainfall results presented in Chapter 4, section 4.2.6 (Table 4.2, p74). Furthermore, January and April showed no change, which was also reflected in the LAPGRD results. There was, however, a small discrepancy between the LAPGRD and cycleplot results for August and November.

The seasonal shifts demonstrated here are problematic for areas with acid sulfate soils. Once the pH of the soil drops below 4, the reduction of Fe II to Fe III by *T. ferrooxidans* is temperature-dependent and is the driving force responsible for the oxidation of ASS with considerable quantities of Fe III often produced (Bloomfield and Coulter, 1973). A late dry summer provides opportunistic conditions for increased acid production through watertable lowering and higher temperatures, while a month of heavy rainfall following a dry spell provides a process for the mobilisation of acid and Fe III to surface waters. It is important to note that the maximum day-time temperature for late summer (i.e., January and February) is higher than at any other time during the year. Table 6.4 shows the average maximum day-time temperatures for the Tweed Catchment. The average maximum temperature has a range from 28.1°C for February to 20.5°C for July.



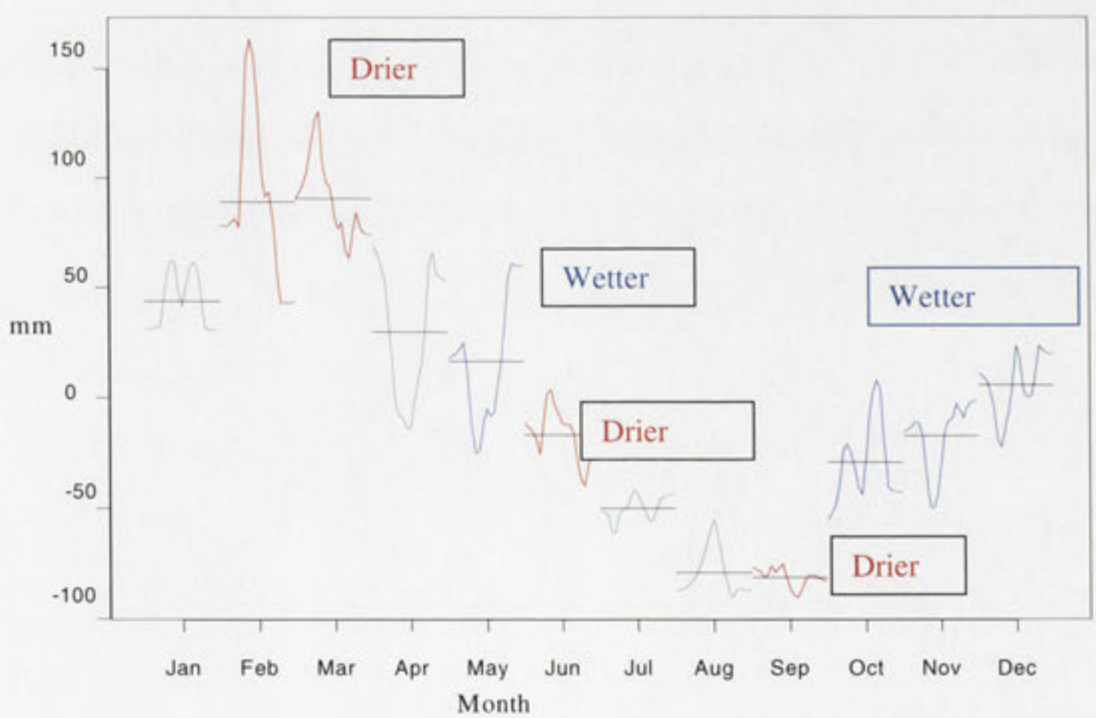
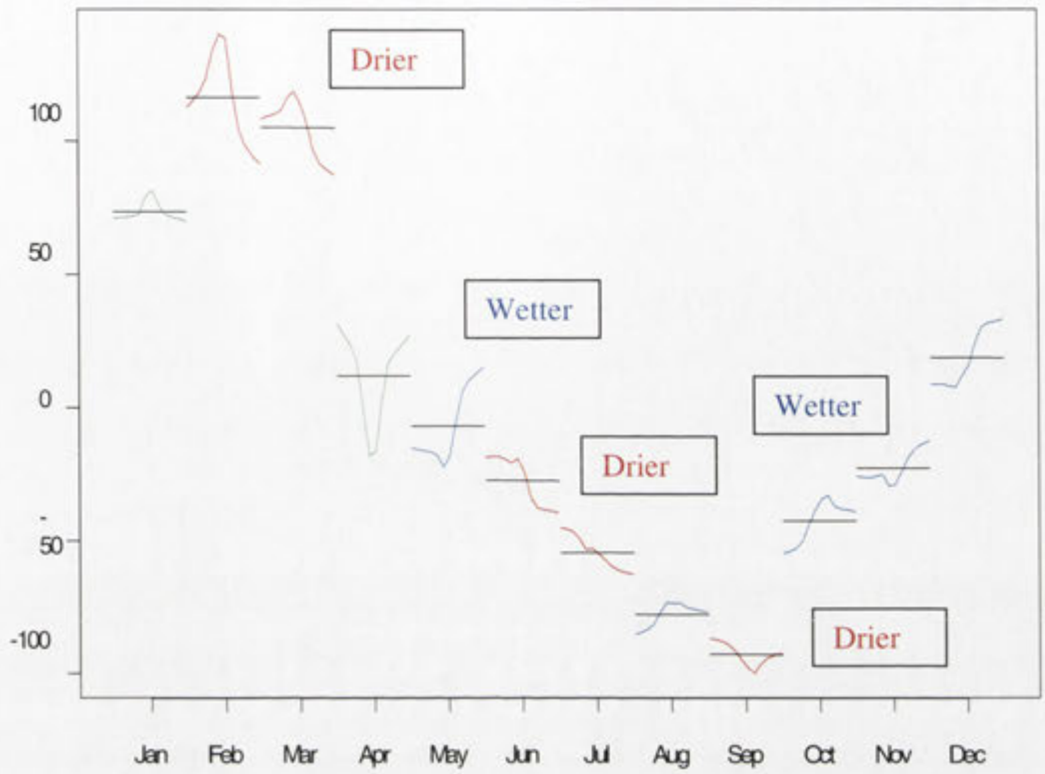


Figure 6.14 Monthly Seasonal Component of Rainfall from 1920 to 2000 for Tweed Heads, cycleplots of very long-term smoothing (top graph) and long-term smoothing (bottom graph).

Drier No Change Wetter



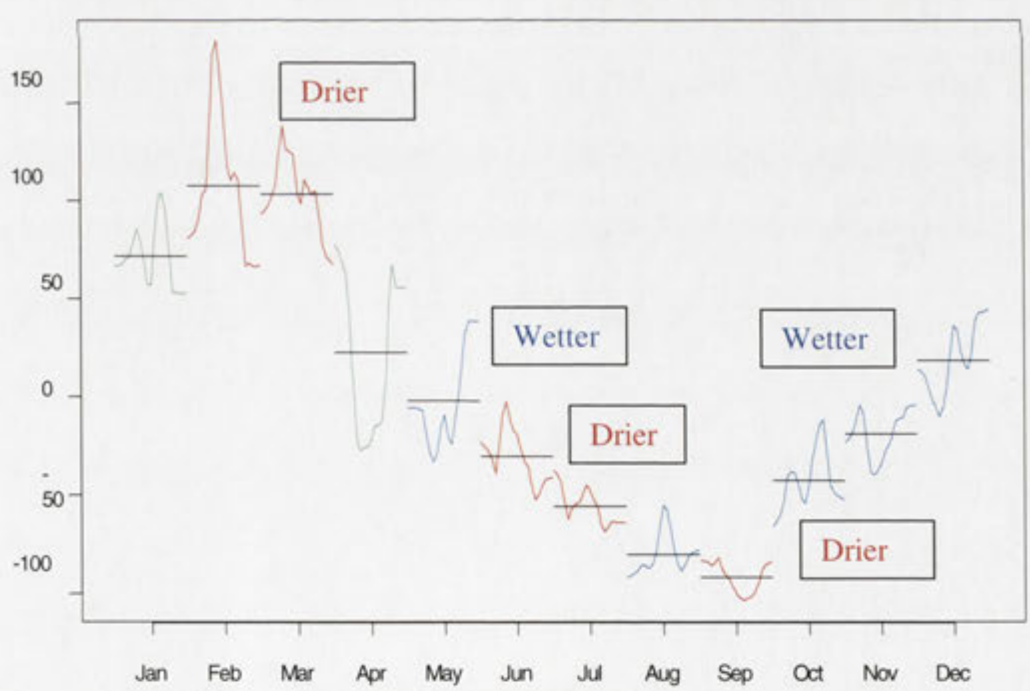


Figure 6.15 Monthly Seasonal Component of Rainfall from 1920 to 2000 for Murwillumbah, cycleplots of very long-term smoothing (top graph) and long-term smoothing (bottom graph).

Drier No Change Wetter

Table 6.4 Average of Daily Maximum Temperature in degrees Celcius for the Tweed Catchment (Bureau of Meteorology, 2003b).

Month	Maximum Average Daily Temperature °C
January	28.0
February	28.1
March	27.6
April	25.9
May	23.4
June	21.1
July	20.5
August	21.1
September	22.7
October	23.8
November	25.5
December	27.5

6.4.4 Seasonal Component in Two Dimensional View

To explore changes in the seasons through the years it is important to be able to view these changes by comparing the monthly seasonal pattern down through the years. This is achieved by ordering the data into a two dimensional (2D) month by year format. This is simply another form of visualisation using the STL package in S-Plus to identify the important features associated with seasonal variation. Variation in the intensity of seasonal rainfall throughout the years is portrayed by contours in association with changes in colour intensity or tinting. For example, dark blue signifies high rainfall seasonality while red tinting indicates varying degrees of low rainfall or extreme dry. A shift in seasonal activity is easily detected using this method simply by looking for changes in the intensity and location of the tinting.

The 2D seasonal component for Tweed Heads and Murwillumbah from 1920 to 2000 (Figure 6.16 a and b), provides a visual account of the changes in seasonality over the last

80 years of record. There is a distinct change in the seasonal pattern during the early 1980's with a shift in rainfall activity from January and February to March, April and May. This distinct shift in rainfall seasonality was accompanied by a moderately intense seasonal rainfall pattern around the 1990s. The months of January and February displayed a weak seasonal rainfall from the period 1980 through to 2000. Periods of strong seasonal rainfall were also apparent around the mid-1950's and 1970's. These time periods included the large floods of 1954 and 1974 which prompted the constructed of levees around the townships of Murwillumbah and Lismore (Tweed Link, 2002). The 1954 February floods, a result of cyclonic weather, passed through Tweed Heads dumping 900 mm of rainfall in less than 24 hours. Twenty-six people lost their lives as a result of this extreme weather event and vast regions of northern coastal low lands were inundated with floodwaters for several weeks (Bureau of Meteorology, 2003b).

The 2D seasonal component for Murwillumbah, shown in Figure 6.17, provides a more detailed historical account of the change in seasonality over a longer time scale. Once again, as with the long-term components presented in section 6.4.2, the 2D view for Murwillumbah reveals a distinct seasonal rainfall pattern. It is interesting to note, that as well as a seasonal rainfall shift in the 1980's, there was also a shift during the early 1920s to the late 1930's. However, this shift does not appear to be as pronounced as the shift that occurred during the 1980's and 1990's. The extremely dry pattern beginning to take effect around the years 1999 and 2000 at Tweed Heads (Figure 6.16 b) is also of particular interest.

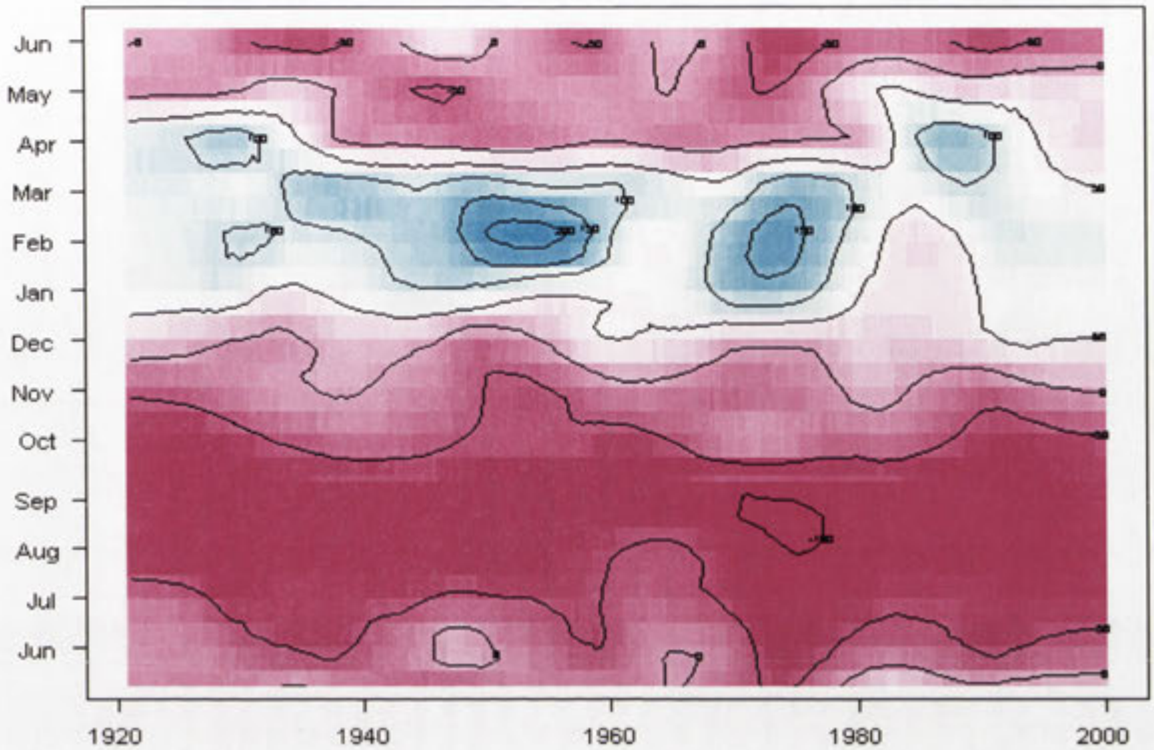
For eastern Australia, an El Niño event or a negative SOI value is associated with an increased probability that climatic conditions will be much drier than normal (Nicholls, 1988). The large and distinct shifts that took place during the 1920's, 1930's, 1980's and 1990's and the fact that certain months of the year have become wetter or drier over the last 100 years (section 6.4.3), may suggest that long-term changes in global weather patterns have occurred. Some evidence suggests that the frequency of ENSO events has been increasing since the 1980's (Fedorov and Philander, 2000). Climatologists also noticed a sudden shift in circulation patterns that occurred in 1976 which may have switched the equatorial Pacific into a "quasi-permanent ENSO state "(Burroughs, 1997). Despite various hypotheses, there is no evidence to suggest that there is link between ENSO events and global warming. Furthermore, the fact that a change in seasonality had also occurred during the 1920's and 1930's, suggests that changes in rainfall seasonality may be more closely connected with natural changes in global climate patterns and have no direct association with anthropogenic activities.

Palaeoclimate studies, which investigate climate variability on millennial time-scales, provide an accurate and informative snapshot of ENSO variability over longer time periods (Tudhope *et al.*, 2001). It has been shown recently that high and low ENSO activities alternate at time scales about every 2,000 years (Moy *et al.*, 2002). This study examined sedimentation cores from Lake Pallcacocha, in southern Ecuador, a region strongly influenced by variability in ENSO activity. Based on these findings, it would appear that, if the sedimentation record is accurate, there will be an increase in El Niño events in the early part of this century. Similar studies conducted in the coastal lakes of NSW have revealed similar cyclic patterns with El Niño events reaching a high peak of activity every 1500 to 2000 years (Smith, 2002).

Isotopic dating of coral atolls has also been used for reconstructing a past climate history of ENSO events which would not have otherwise been possible using short-term records based on instrumental measurements (Cole *et al.,* 1993; Fairbanks *et al.,* 1997). The long-term climate records obtained from lake sediments and coral atolls provide a valuable tool for predicting the frequency and severity of El Niño events in the future and would thus provide land managers with the opportunity to plan ahead and develop strategies to reduce the impacts of severe drought. Similar techniques described by Moy *et al.* (2002), could be used to determine the history of ENSO cycles for the Tweed region simply by analysing the sediments in Cudgen Lake.

The 2D seasonal component for Murwillumbah and Tweed Heads also reveals that the rainfall seasonality shifts and intensities are maintained over a period of approximately ten years or more. This suggests that these patterns operate on decadal time scales. However, El Niño and La Niña events alternate every 2 to 8 years, lasting for a period of between 6 to 18 months. Therefore, any relationship between shifts in seasonality of rainfall in the northern NSW and ENSO events appears tenuous.

(a)



(b)

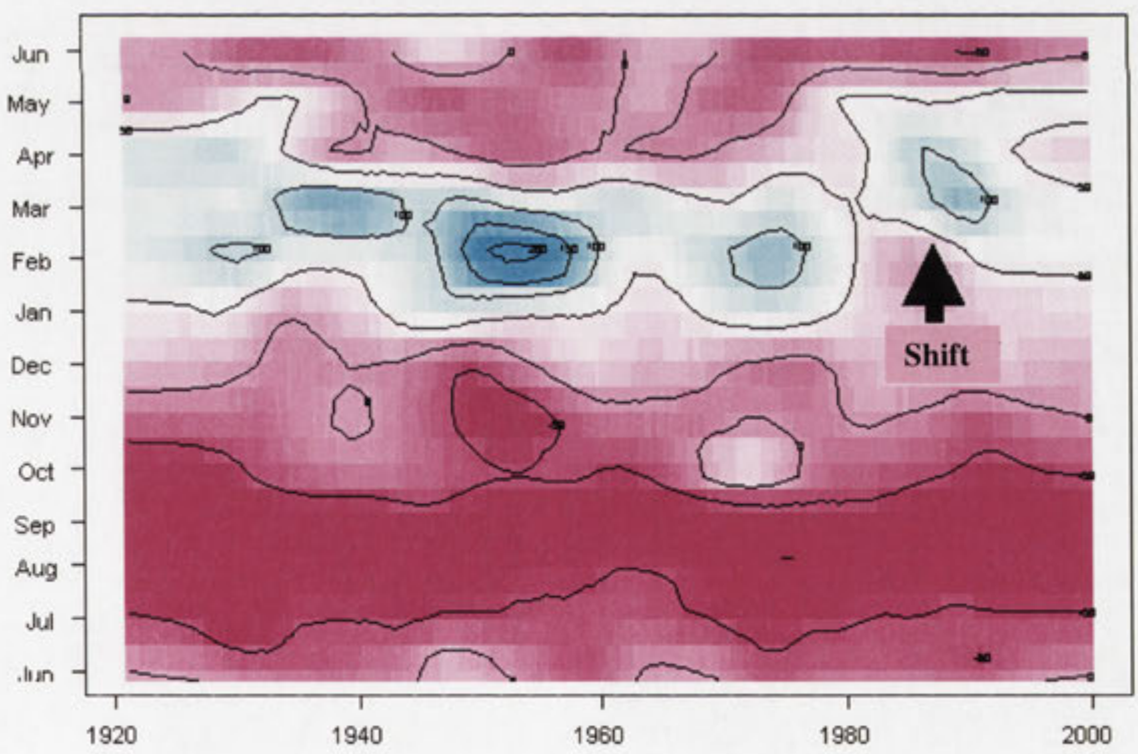


Figure 6.16 2D Seasonal rainfall component for (a) Murwillumbah and (b) Tweed Heads from 1920 to 2000 showing the distinct seasonal shift since the 1980's.

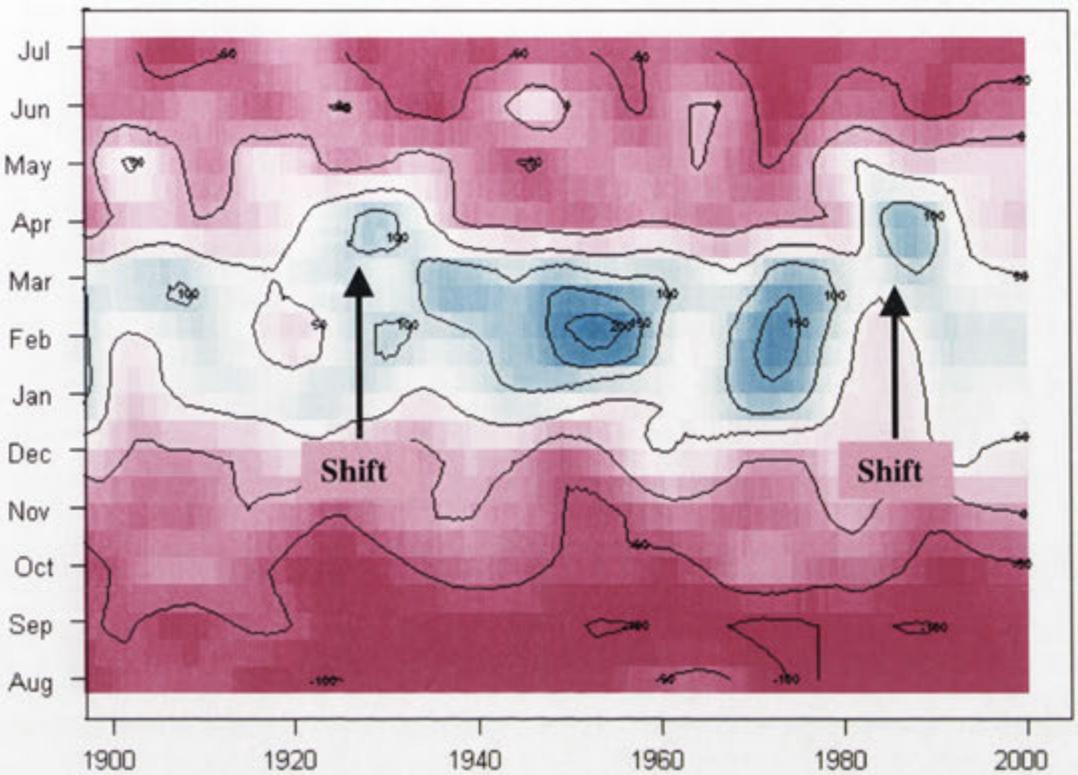


Figure 6.17 2D Seasonal rainfall component for Murwillumbah from 1900 to 2000.

6.5 Seasonal Variability and the Pacific Decadal Oscillation

Numerous reports describe interdecadal climate fluctuations in the North Pacific basin (Mantua *et al.*,1997; Cayan,1996; Latif and Barnett, 1994) and the connection between interdecadal climate variability in the North Pacific and changes in marine ecosystem dynamics (Francis and Hare, 1994). These North Pacific climate anomalies are attributable to the Pacific Decadal Oscillation (PDO) (Power *et al.*,1999b). The PDO is also referred to as the Inter-Decadal Pacific Oscillation (IPO)(Mantua *et al.,* 1997).

The PDO has a similar climate signature to the Southern Oscillation with two main differences. Firstly, their length of cycle is quite different. Typically, PDO events can be measured in decadal time scales often prevailing for time periods of 20 years or more, whereas ENSO events persist for only 6 to 18 months (Mantua *et al.,* 1997). Secondly, unlike the ENSO climate signature, the signature of PDO occurs mostly in the North Pacific/ North American sector, although it is not that uncommon for secondary signatures to also occur in the tropics (Zhang *et al.*,1997). Variations in the PDO are measured using indices constructed from patterns observed in the Sea Surface Temperatures (SSTs) and Sea Level Pressures (SLPs). A positive index is obtained for both SSTs and SLPs when the SSTs are anomalously cool in the interior North Pacific (with warm conditions along the Pacific coast of America) and when the SLPs exhibit below average readings (Mantua, 2002). A positive index is commonly referred to as a 'warm phase'. One notable feature of the PDO indices is the long duration of the warm and cool phases which often prevail for 15 to 30 years. A negative index or cool phase occurred between 1945 and 1957 with another one between 1965 and 1980.

Several studies have documented the impacts of climate variability in response to changes in the PDO. It has been shown that North America streamflow and snow fall anomalies have been closely linked to PDO cycles (Cayan, 1996), while in the US, there is an apparent PDO effect on summer rainfall and drought (Nigam *et al.*, 1999). These climate anomalies have also had a major impact on marine ecosystems. For example, a warm PDO phase is favourable for salmon production in Alaska, while a cool PDO phase often results in low salmon production off the west coast of California and Oregon (Francis and Hare, 1994; Mantua *et al.*,1997).

The literature suggests that the PDO is typically a North Pacific phenomenon, however it would also appear that this has some relevance to ENSO activity as well. For example, North American climate anomalies, which have a strong relationship with PDO events, also have strong similarities to those associated with El Niño and La Niña, although not as extreme (Latif and Barrett, 1996). If this is the case, then it is possible that there is a relationship between the PDO and climate variability for coastal regions of eastern Australia. Decadal variations in the Australian climate that are closely connected with the SOI, have been reported by various authors (Wang and Ropelewski , 1995; Power *et al.*, 1999a; Power *et al.,* 1999b). Power *et al* (1999b) showed that Australian rainfall displays an 'in phase' relationship with the SOI on decadal time scales. They concluded that, when the central eastern Pacific is in a warm phase there is a tendency for parts of eastern Australia to be warm and dry. However, they also showed that there is a tendency for the PDO to be 'out of phase' with Australian rainfall ($R< -0.4$) but 'in phase' with temperature ($R>0.4$) for most parts of eastern Australia. A related study showed that there was a significant correlation ($R = 0.7$, $R^2 = 0.49$) between Australian rainfall variability and SOI when the PDO was negative (Power *et al.*,1999a). In contrast, they found that there was no correlation ($R = 0.1$, $R^2 = 0.01$) between rainfall variability and SOI when the PDO was positive. It is also interesting to note, that when the SST of the Pacific is warm, ENSO cycles tend to be more frequent with higher amplitude (Wang and Ropelewski, 1995). Despite the variation in correlations between Australian rainfall and the PDO, all of these studies have basically reached the same conclusion that PDO modulates the strength of El Niño and La Niña events. Therefore, although it might be tempting to draw a direct correlation between PDO and rainfall variability for eastern Australia, it is far more practical to examine this relationship in context with the SOI, since the effects of ENSO on Australian climate are influenced by the PDO.

A correlation between SOI and PDO was carried out by taking the moving averages for time periods ranging from 3 to 233 months. This treatment results in progressive smoothing of the data as the time period is increased. The correlation coefficients between SOI and PDO for progressively smoothed data from 1900 and 2000 is shown in Figure 6.17. Figure 6.18 shows the relationship between PDO and SOI smoothed over a 12 month period. These results clearly show that there is a negative correlation between SOI and PDO. In other words, when the PDO is positive, the SOI is negative.

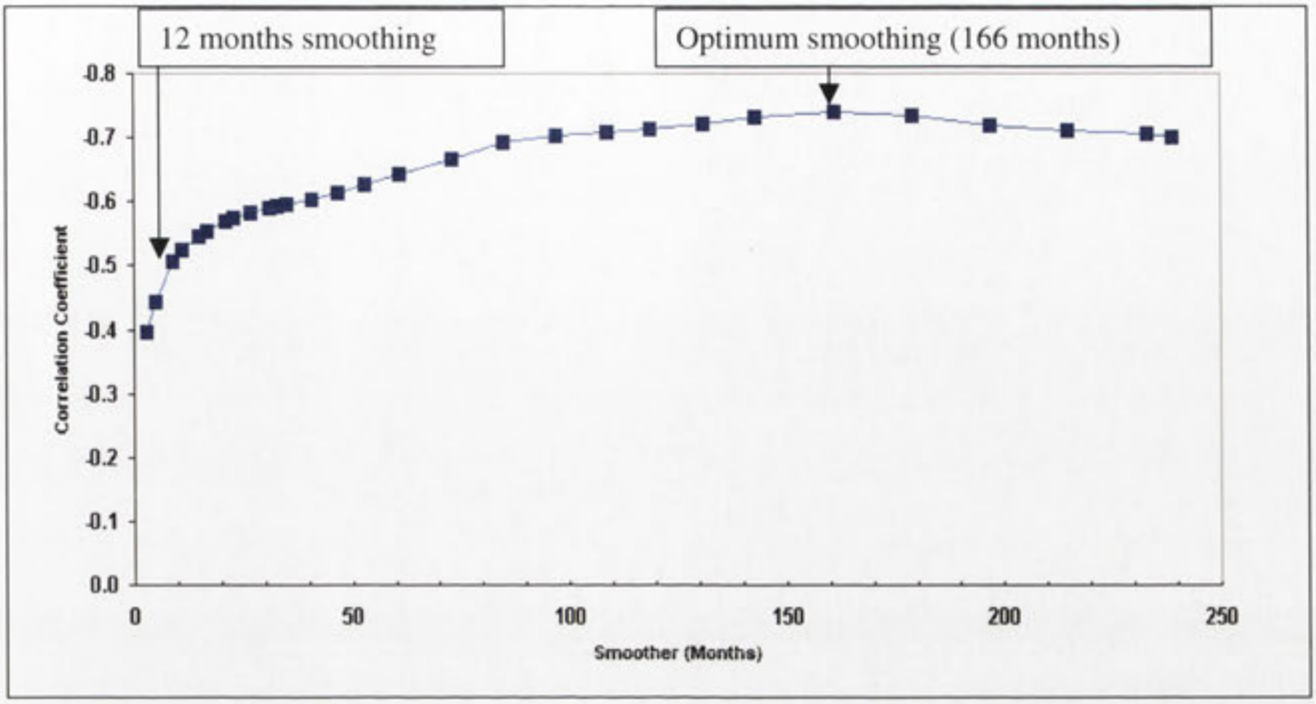


Figure 6.17 Correlations between SOI and PDO for progressively smoothed data.

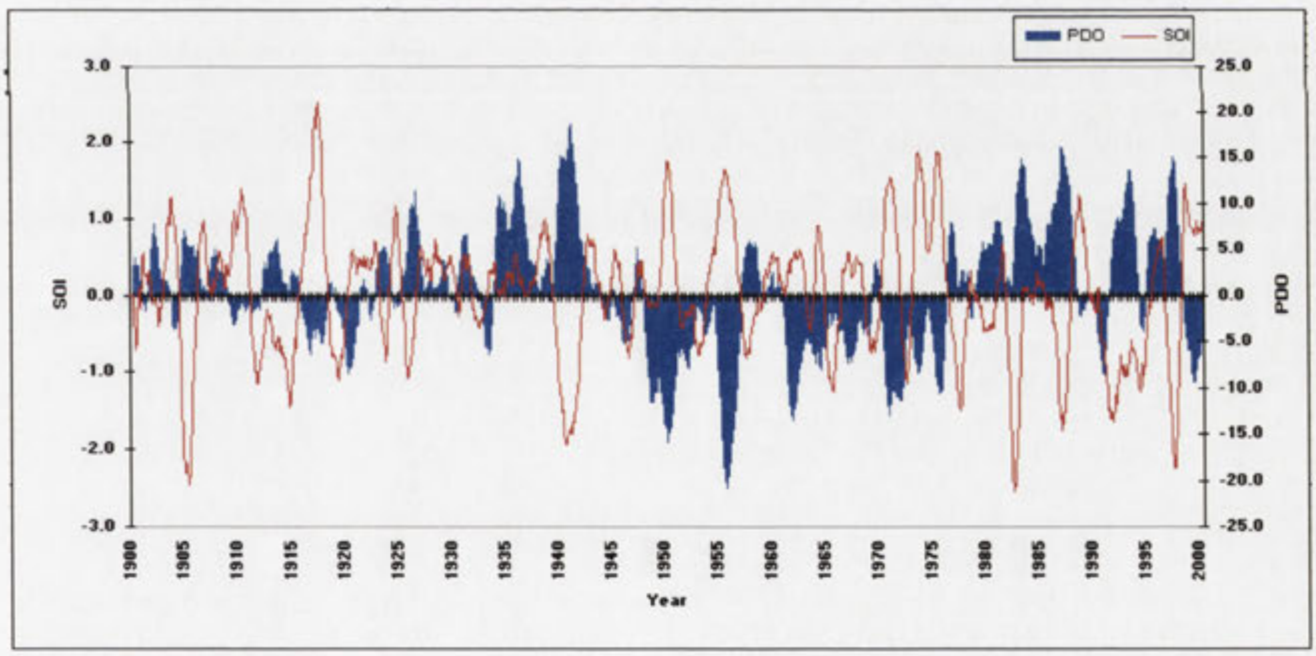
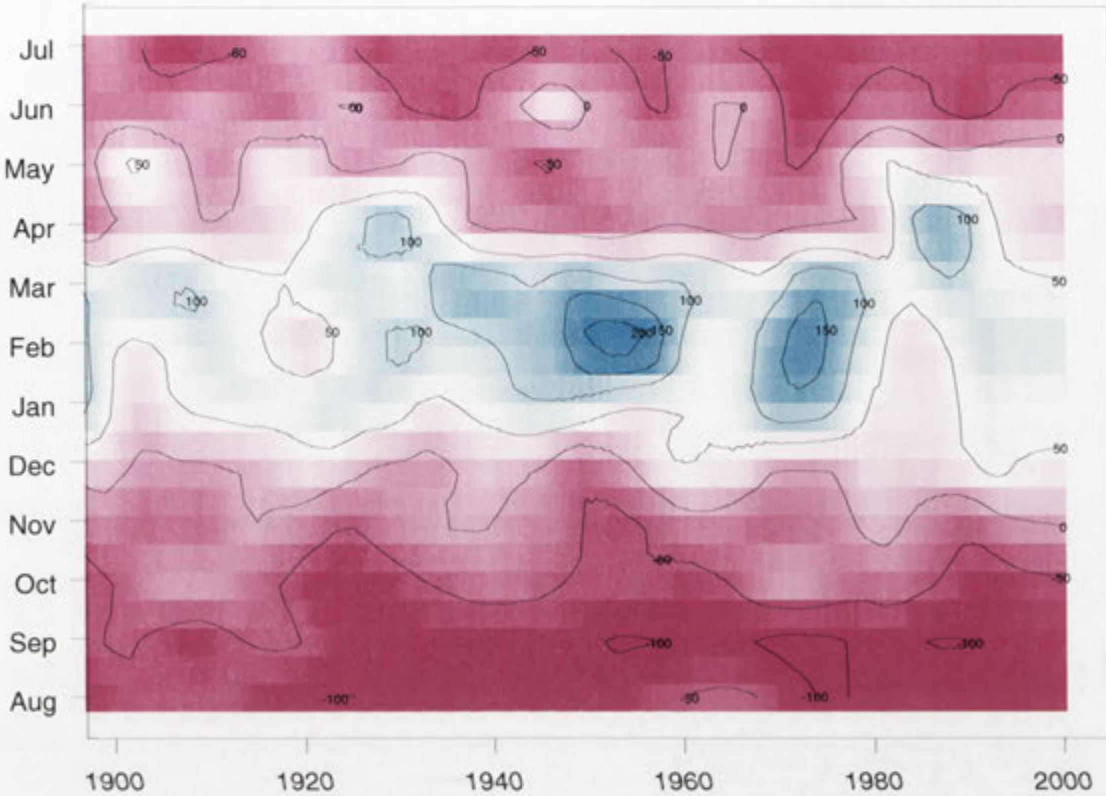


Figure 6.18 Relationship between PDO and SOI smoothed over 12 month period.

The best 'negative' correlation between SOI and PDO was obtained (correlation coefficient, R = -0.73) after 166 months or 13 years of progressive smoothing (Figure 6.17), which represents around one decadal cycle. Overall, there was good 'negative' correlation between SOI and PDO for all months of smoothing including 12 months of smoothing (correlation coefficient, R = -0.52) (see Figure 6.17). Figure 6.19 shows the relationship between 2D seasonal rainfall better at Murwillumbah and the 166 months of smoothing of the PDO and SOI. Examination of the results shown in Figure 6.19 suggests that there is a reasonable correlation between rainfall variability and the PDO. Based on these observations, it would also appear that there is a strong association between a positive PDO and a shift in rainfall seasonality. Furthermore, high rainfall events appear closely correlated with negative troughs in the PDO.

To investigate the relationship between PDO and rainfall variability in more detail, a percentage ranked correlation was carried out between 166 months of smoothed rainfall data and the PDO (Figure 6.20). This smoothing period was chosen because it gave the best correlation between SOI and PDO (see Figure 6.17). A correlation between SOI and rainfall during different phases of the PDO was also examined using the same smoothing period. The results presented in Figure 6.21 show that there is a strong negative correlation (R = -0.55) between rainfall and the PDO. Of particular interest is the correlation between SOI and rainfall for the different phases of the PDO. Rainfall was found to be significantly correlated with the SOI (R = 0.86) only when the PDO was negative (Figure 6.22 b). There was no significant correlation (R = 0.36) between rainfall and SOI when the PDO was positive (Figure 6.22 a). These results are consistent with the conclusions of Power *et al* (1999a) which suggest that, assuming a linear and lagged relationship between SOI and rainfall, the ability to predict the seasonal variability in Australian rainfall is greatly enhanced when the PDO is negative. It is also noted that the lowest rainfall over the 166 month period occurs at the peak of the PDO.

The results clearly demonstrate that the inter-annual climate variability caused by ENSO is masked by a much longer climate variability measured on decadal time scales. Prolonged dry and wet periods often have devastating impacts on agricultural production (Smith *et al.*, 1992). The ability to forecast climate variability on decadal time scales with some degree of skill would be beneficial to farmers and catchment managers. Policymakers could use this type of information to plan for long-term strategies that would minimise the impact of seasonal variability on acid discharge events. Although a considerable amount of work has examined the ecological impacts associated with changes in the PDO, its mechanisms are still poorly understood (Mantua, 2002). The ability to accurately forecast climate predictions for periods of ten years or more requires a better understanding of the processes that gives rise to the PDO. The results presented here clearly highlight the need for improved climate prediction models, similar to the coupled global ocean atmosphere model developed by the Bureau of Meteorology Research Centre (Wang *et al.,* 2000). Further investigation into the association between ENSO and seasonal variability during various phases of the PDO is also required.



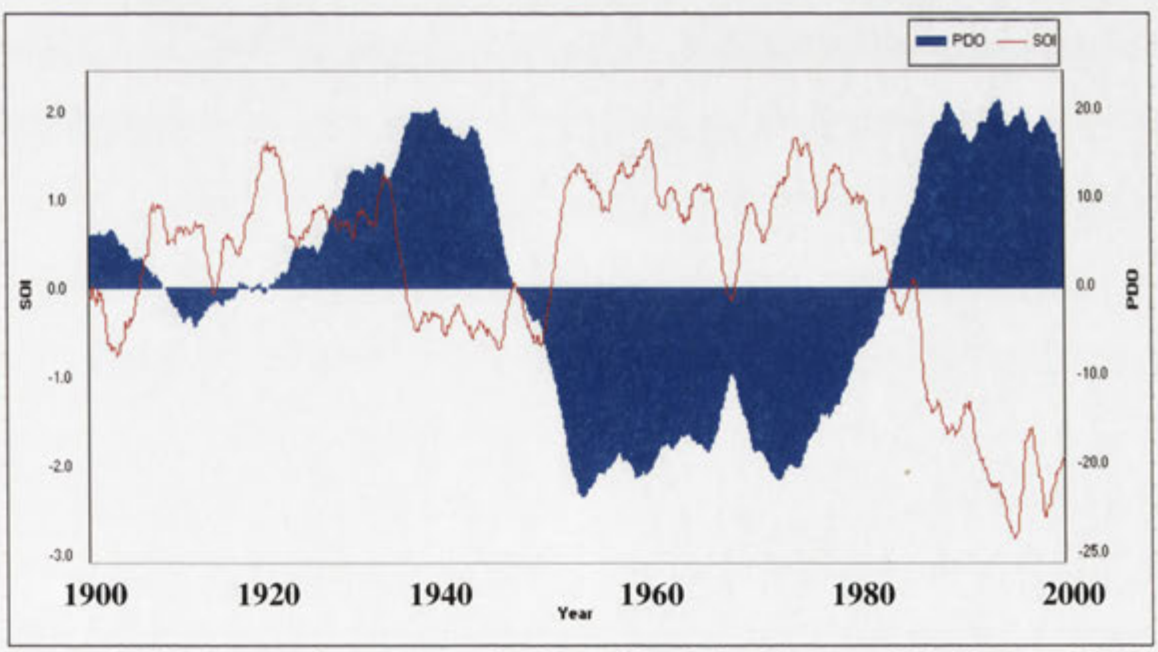


Figure 6.19 2D Seasonal component for Murwillumbah (above) and the PDO and SOI smoothed over 166 months (below).

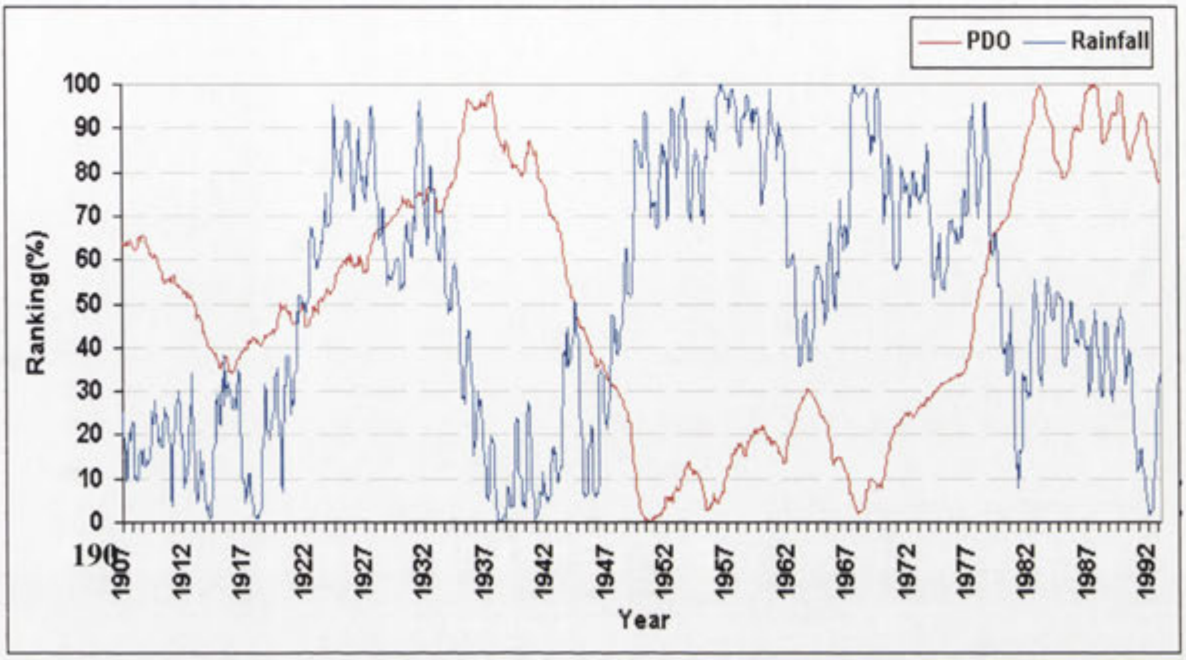


Figure 6.20 Ranked correlation between PDO and rainfall using 166 months smoothing period.

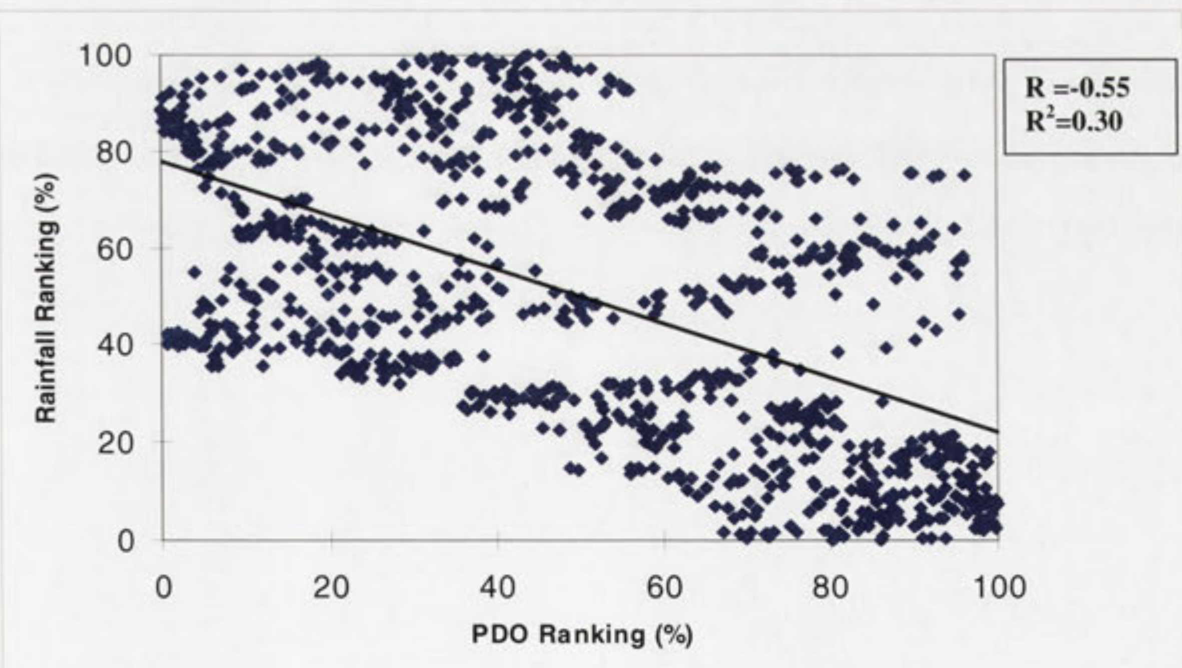
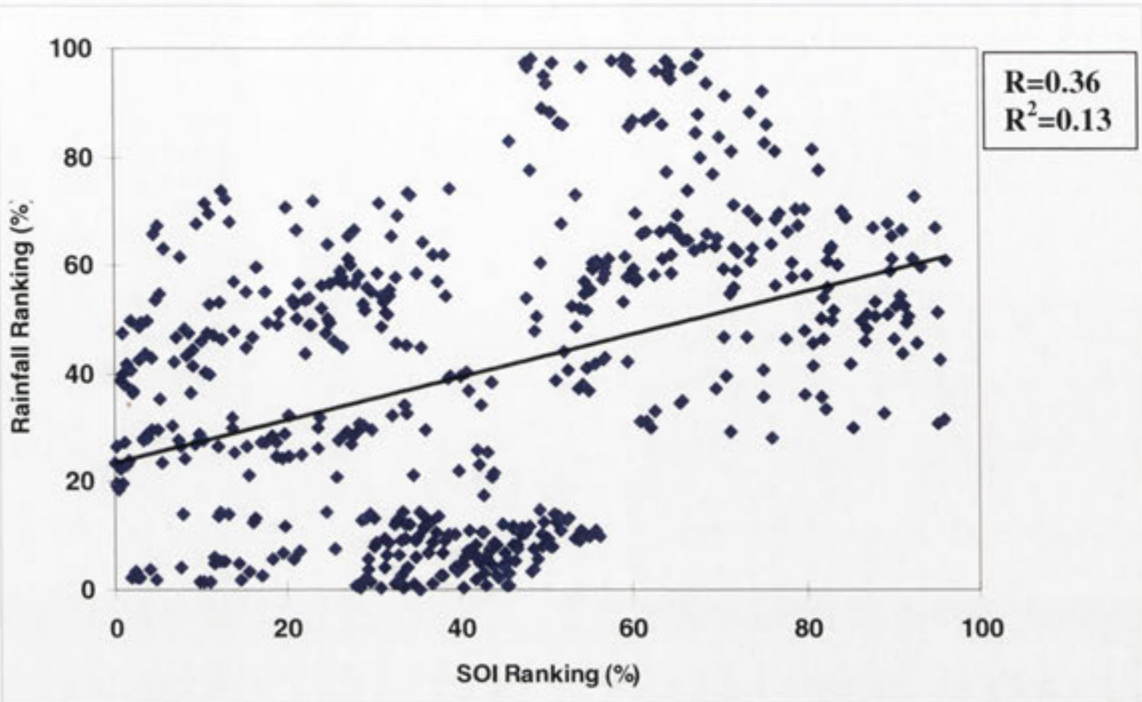


Figure 6.21 Correlation between rainfall percentile ranking and PDO percentile ranking.

(a)



(b)

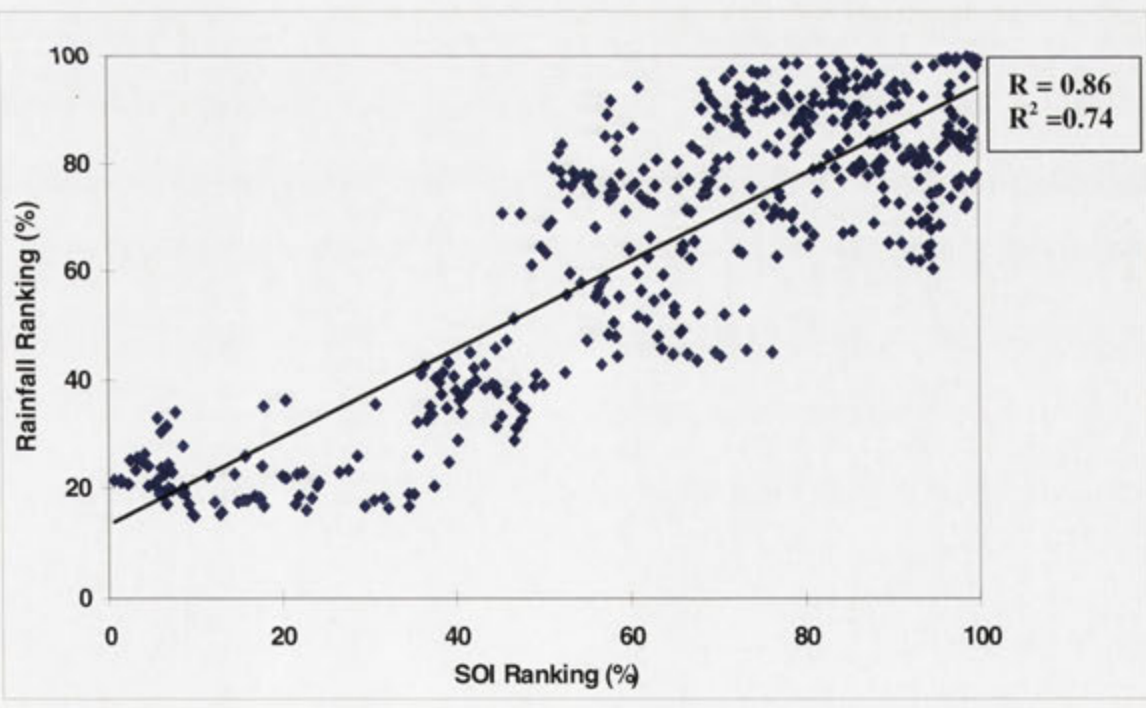


Figure 6.22 Correlation between rainfall percentile ranking and SOI percentile ranking for the (a) positive and (b) negative phase of the PDO.

6.6 Discussion and Summary

The climatic events that are responsible for changes in water quality and acid discharge events are complex. However, the analysis of the long-term rainfall data using deciles and percentiles as well as other non-parametric smoothing methods, such as STL, provide insight into rainfall variability in the Tweed Catchment. The analysis of rainfall data using deciles and percentiles is an excellent method for gauging the severity of extreme events over the length of the historical record.

Changes in the Australian rainfall are greatly influenced by changes in the global systems, the Southern Oscillation (SO) and the Pacific Decadal Oscillation (PDO). Unfortunately, Australian rainfall records provide only a short history of variability (~100 years). Over the last one million years, the world's climate has experienced dramatic events ranging from glacial to interglacial periods, at intervals of around 100,000 years (Bryant, 1997). The ability to confidently predict future climate variability using rainfall records is a challenge, despite the various sophisticated techniques currently available. The ability to predict an El Niño event on a six year cycle is around 50% (R^2= 0.51). The results presented here have shown that the correlation between rainfall and the SOI for the Tweed is greater when the PDO is negative (R=0.86, R^2 = 0.73). However, there was no correlation between rainfall and the SOI when the PDO was positive (R=0.36, R^2 = 0.13).

The cycleplot analysis revealed that conditions in the Tweed have become drier for the late summer and early autumn months (i.e, February and March) and wetter conditions for May. A shift towards higher rainfall was also evident for October, November and December. These changes were the same for both short and long-term smoothing. It is interesting to note that the shift towards drier conditions for February, March, June, and September and an increase in rainfall for May, October and December was also reflected in the LAPGRD analysis of the short-term spatial rainfall discussed in Chapter 4 (section 4.2.6). It was found that this change in seasonality occurred in the early 1980's. There was no change in the seasonal rainfall component for January and April, which was also reflected in the LAPGRD results. According to the cycleplot results for Tweed Heads, there was no change in the seasonal rainfall component for January, April, July and August. However, Murwillumbah revealed drier conditions for July with slightly higher rainfall for August.

A late dry summer, coupled with wetter conditions during late autumn, are highly favourable for both the formation of acidic products in acid sulfate soils and their subsequent discharge into aquatic ecosystems. Since acid production is a temperature dependent process, a combination of a dry summer and a low watertable results in the rapid build up of acid reserves within the soil profile. Heavy rainfall during the late autumn months raises the watertable levels and initiates the translocation of acid reserves to the surface waters. The rainfall seasonality changes as presented in this chapter, operate on decadal time scales and are strongly influenced by the PDO.

The development of a stochastic climate model, which couples PDO, rainfall variability and ENSO information, may enhance future long-term forecasts. Unfortunately, rainfall and climate data collected from weather stations in the Tweed (and for that matter in Australia) offers little insight into the long-term climate variability due to the short length of record (>150 years). Paleoclimate records provide a more detailed history of climate events on which future climate predictions could be based and is, therefore, worthy of future research. Sedimentation cores, taken from coastal lakes such as Cudgen Lake, could provide a comprehensive picture of past climate events in the region than would be possible using climate data derived from weather stations.

In view of these findings, there is a need for land management policies that support long-term water quality monitoring programs and encourage the implementation of land management practices which will accommodate the impacts of long-term climate change. The long-term impacts of global warming on climate change is still being investigated. Predictions indicate that a 0.25 m rise in sea level is possible due to climate change within the next 50 years (IPCC, 1990). A rise of this magnitude would have considerable implications in low-lying areas of coastal floodplains. Policies for floodplain management in eastern Australia have yet to be developed for this expected rise in sea levels.

CHAPTER 7
Rainfall Variability and Fish Kills

Chapter 7. Rainfall Variability and Fish Kills

7.1 Introduction

There is often considerable speculation surrounding fish kill events in coastal waters following a period of heavy rainfall. People have often blamed pesticides washed into the river system from cane and banana plantations as the primary cause of fish kills (Easton, 1989). However, previous work has clearly shown that the release of acid and acid by-products into estuarine environments from ASS landscapes is one of the leading cause of fish deaths in ASS floodplains (Sammut *et al.*,1996). Mortality and morbidity studies involving fish populations, have linked fish kills in acid sulfate soil regions with seasonal changes, often occurring during a transitional period from a dry to a wet season (Brown *et al.*, 1983; Callinan *et al.*,1993; Sammut *et al.*, 1996). It has also been shown that acid and acid products can reach levels that are toxic to fish and other aquatic life after periods of heavy rainfall (Sammut *et al.*, 1996; Callinan *et al.*, 1993). The water quality results presented in section 5.5 (Chapter 5), suggests that the timing of a fish kill event was associated with a build up of acid during a dry spell followed by heavy rainfall sufficient to initiate acid groundwater discharge.

An examination of the water quality records for Cudgen Lake had revealed that significant fish kills occurred during August 1998 and late May to early June 1991 (Eastern C, personal communication, 2002). According to Easton (1992), extensive rainfalls occurred over the Cudgen Lake Catchment during May/June 1991, resulting in highly acidic water (pH 2.5) and dissolved aluminium (around 60 ppm). It was believed that a major contributing factor for such a large and significant acid outflow event, was the recent drainage works carried out in the Tanglewood area of the Cudgen floodplain. The aquatic life affected by this event included juvenile fish species as well as prawns. Large numbers of mullet had left the lake environment on their annual spawning run prior to the acidification event (Easton, 1992).

A second fish kill event also took place during mid December 1991 in both the Tweed and Cudgen Catchments; however, the timing of these fish kill events was shown to be different. Water quality data showed that acidification of the Tweed and Rous Rivers took place several days after the Cudgen acidification event (Easton, 1991). Fish kills have also taken place in the Tweed prior to 1991. A very large fish kill event took place in the Tweed River during March 1987 following a three-year drought.

Water quality monitoring is useful in assessing the severity and extent of an acid discharge event in response to a range of climatic conditions. However, the development of a climate indicator for predicting fish kills using available rainfall data would not only complement the monitoring process, but would also greatly assist in predicting fish kills in catchments where there are no monitoring sites. In addition, it would also aid in the implementation of land management strategies which could be used to reduce the impact of major acidification events at the catchment scale, especially if climate variability is also considered.

7.2 Water Quality and Aquatic Life in the Cudgen Catchment

The health and condition of an aquatic environment can be also be measured by the presence or absence of aquatic life. Macroinvertebrates are commonly used as biotic indicators for assessing the health of aquatic ecosystems and are good indicators for determining the capacity of the environment to support other life forms, including fish populations (Howells, 1990). Low pH waters can create unfavourable breeding and feeding habitats for many fish species as acid waters can affect predator numbers, including macroinvertabrates, especially if acidification events occur on a regular basis (Sammut *et al.*,1996). In some European lakes, fish populations have undergone a steady decline in water which is constantly affected by acid runoff (Egglishaw *et al.*, 1986; Stonner and Gee, 1985). However, many of these studies have also revealed that there may be other determining factors associated with fish mortalities besides low pH. For example, changes in water chemistry and dissolved oxygen levels impact upon fish survival rates (Sammut *et al.* , 1996).

Aquatic life is very sensitive to small changes in pH and dissolved aluminium concentrations. For fresh water biota, the recommended pH range is 6.5-9.0 (Sammut *et al.*, 1996). A small change in pH can also be accompanied by significant changes in the water chemistry. When the pH of the water decreases there is an increase in the solubility of ions, such as, iron and aluminium. Because aluminium is extremely toxic to gilled organisms, standards have been established as a guide for determining what levels are detrimental to living organisms. The Australian Water Quality Guidelines for Fresh and Marine Waters set down by the Australian and New Zealand Environment and Conservation Council (ANZECC) recommend that the concentrations of aluminium should not exceed 5.0 μgm/L when the pH is less than 6.5 (Anon, 1992). Aluminium concentrations in Cudgen Lake have exceeded the ANZECC guidelines on a number of occasions since monitoring commenced (WBM Oceanics, 1998).

Cheers (1992) examined the effects of runoff from acid sulfate soils on benthic communities in Cudgen Lake and Cudgen Creek. Her study showed that benthic organisms are poorly represented in Cudgen Lake and vary in number and distribution across the lake. WBM Oceanics Australia (1998) prepared a summary on the distribution of benthic communities in Cudgen Lake (Figure 7.1) based on the study by Cheers (1992) and concluded, that the greatest number and species of benthic organisms were at the eastern end of the lake, near Cudgen Creek, or in the open waters where there are few or no aquatic reeds. The types of benthic organisms that were recorded during the study included oligochaete worms, spionid polychaete worms, amphipods and chironomid larvae. The low benthic life in some regions of the lake may in part be due to the low levels of dissolved oxygen in the water and bottom sediments of the lake (WBM Oceanics Australia, 1998). The acid tolerant reed *Schoenoplectus littoralis,* which now grows extensively throughout the lake, is partly responsible for creating these anaerobic conditions. Other factors that greatly affect the distribution of benthic communities in the lake, include the discharge of ferrihydrite floccs (Figure 7.2) and dissolved aluminium into the lake. Ferrihydrite floccs smother lake and river beds as well as lowering dissolved oxygen levels.

Apart from the presence of benthic communities, the lake environment is also a habitat for a variety of fish species. WBM Oceanics Australia (1998) conducted a detailed fish survey on behalf of Tweed Shire Council and by using a combination of gill, seine and dip nets in a range of different mesh sizes, found that a large number and variety of fish inhabited the open waters of the lake. These included flathead, (*Platycephalus* *fuscus)*, Mosquito fish (*Gambusia affinis*), Butter bream (*Monodactylus argenteus*), Herring (*Harengula*), Giant Herring (*Elops australis*), Sea mullet (*Mugil cephalus*), Snub-nose gar (*Arramphus scleroepis*), Silver biddies (*Gerres subfasciata*), Cresent Perch (*Terapon jarbua*), Trevally (*Canranx* sp) and Blue-eyes (*Pseudomugil signifer*). The Empire gudgeon (*Hypseleotris compressa)* was also observed in large numbers and although this particular species of fish lives mostly in brackish waters, it also seeks out acid waters, and has been known to adapt to pH levels as low as pH 4.4 (Easton, 2002; White and Melville, 1996). The relative tolerance of some fish species to acidic waters is shown in Table 7.1.

The fish surveys also revealed variations in the density and distribution of fish within the lake, with fish numbers in greater abundance at the south-eastern end of the lake. Since fish generally try to avoid acidic waters, this observation suggests that the water quality in the south-eastern region of the lake where PWD (See Figure 5.24, Chapter 5, p 154) is located is of better quality. The water quality monitoring results presented in section 5.5.3 (Chapter 5) supports this observation. Water quality is generally poorer in those regions where acid waters drain into and out of the lake. At the time of the netting survey, WBM Oceanics Australia also took random water quality measurements at various points in the lake. Although these results were random samples, they showed that the northern and western sectors of the lake were more acidic with pH values in the order of 3.66–4.53, whereas water samples taken at the south-eastern sector of the lake had pH readings around 5.84.

The mosquito larvae *Ochlerotatus vigilax*, responsible for carrying the Ross River Virus, has also been found in large numbers, following periods of heavy rainfall and low pH (Easton, personal communication, 2002). Mosquito larvae can survive in low pH (2) water that would normally be toxic to fish (Easton, 2002). The absence of fish populations also creates perfect breeding conditions for mosquitoes, as mosquito larvae often provides a perfect source of food for fish.

It is surprising to note that, based on these surveys, it is evident that Cudgen Lake supports a diverse range of aquatic life even though the water quality in the lake is generally poor. With this in mind, it is feasible that any slight, favourable change in water quality will certainly contribute to the sustainablity of aquatic life in Cudgen Lake.

Table 7.1 Tolerance levels of fish and mosquito larvae to low pH.

pH Tolerance Level	Species	Comments
6	**Blue Eye (Fish)**	
5	**Gambusia (Fish)**	**Tolerate pH as low as 4.5**
4	***Hypseleotris compressa*** (Native Gudgeon)	**Tolerate pH as low as 4.4**
3		
2	**Mosquito Larvae (i.e., *Ochlerotatus vigilax*)**	**Can survive in water that would normally be toxic to all fish species**

(Source: Easton (2002)

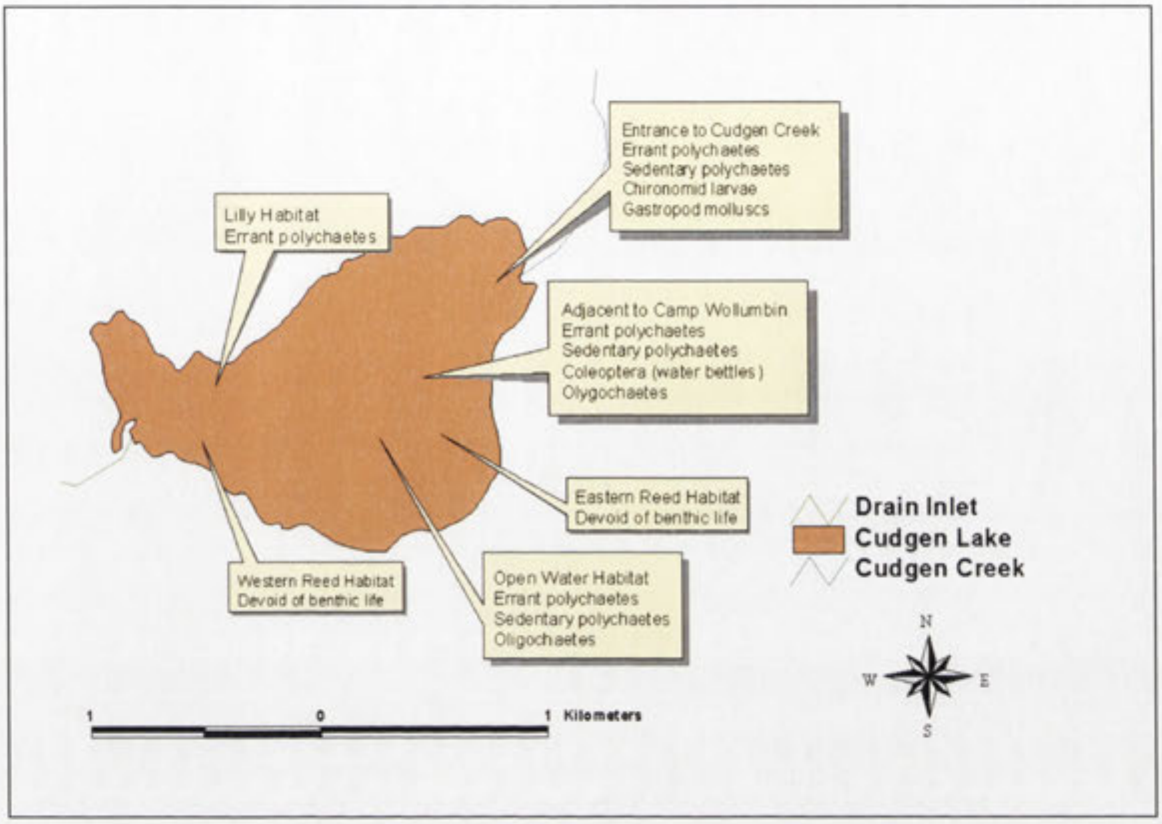


Figure 7.1 Benthic communities in Cudgen Lake (WBM Oceanics Australia, 1998).

Figure 7.2 Cudgen Lake showing ferrihydrite floc indicative of acid outflows. Water flows into the lake from west (bottom left corner) and exits to the ocean via Cudgen Creek (top right hand corner).

7.3 Analysis of Rainfall Surfaces

Rainfall surfaces were generated for the Tweed Catchment to help construct an accurate picture of the climate events leading up to the 1987, 1991 and 1998 fish kill. The rainfall surfaces for individual months, were used to develop a profile of monthly spatial rainfall results against fish kill events. Rainfall surfaces were created using the methodology as discussed in chapter 3 for the individual years 1990, 1991 and 1997, 1998. For the 1987 fish kills, there was a preceding three-year period of below average rainfall that began in 1985 and ended in 1987. To create an accurate picture of the events leading up to the 1987 fish kills, monthly rainfall surfaces were created for all three years leading up to the 1987 fish kills.

Rainfall data from more than 239 rainfall stations located at various sites throughout and surrounding the Tweed and Cudgen Catchments, were used to construct monthly rainfall surfaces. Rainfall stations situated outside the catchment were also included in the construction of the rainfall surface maps, so that a more accurate rainfall surface could be generated from the data. A Fortan program was written to eliminate those stations across the catchment with rainfall records of less than five months. For the various years used in the analysis, the program selected between 239 and 284 stations with at least five or more years of rainfall records. A common smoothing directive was used for each rainfall surface. A list of the all the rainfall stations used in the construction of the climate surfaces is provided in Appendix A. Figures 7.3 a-c show the rainfall surfaces for the year 1991 and Figure 7.4 a-c shows the rainfall surfaces for 1998. The 1985, 1986 and 1987 rainfall surface maps are shown in Appendix C.

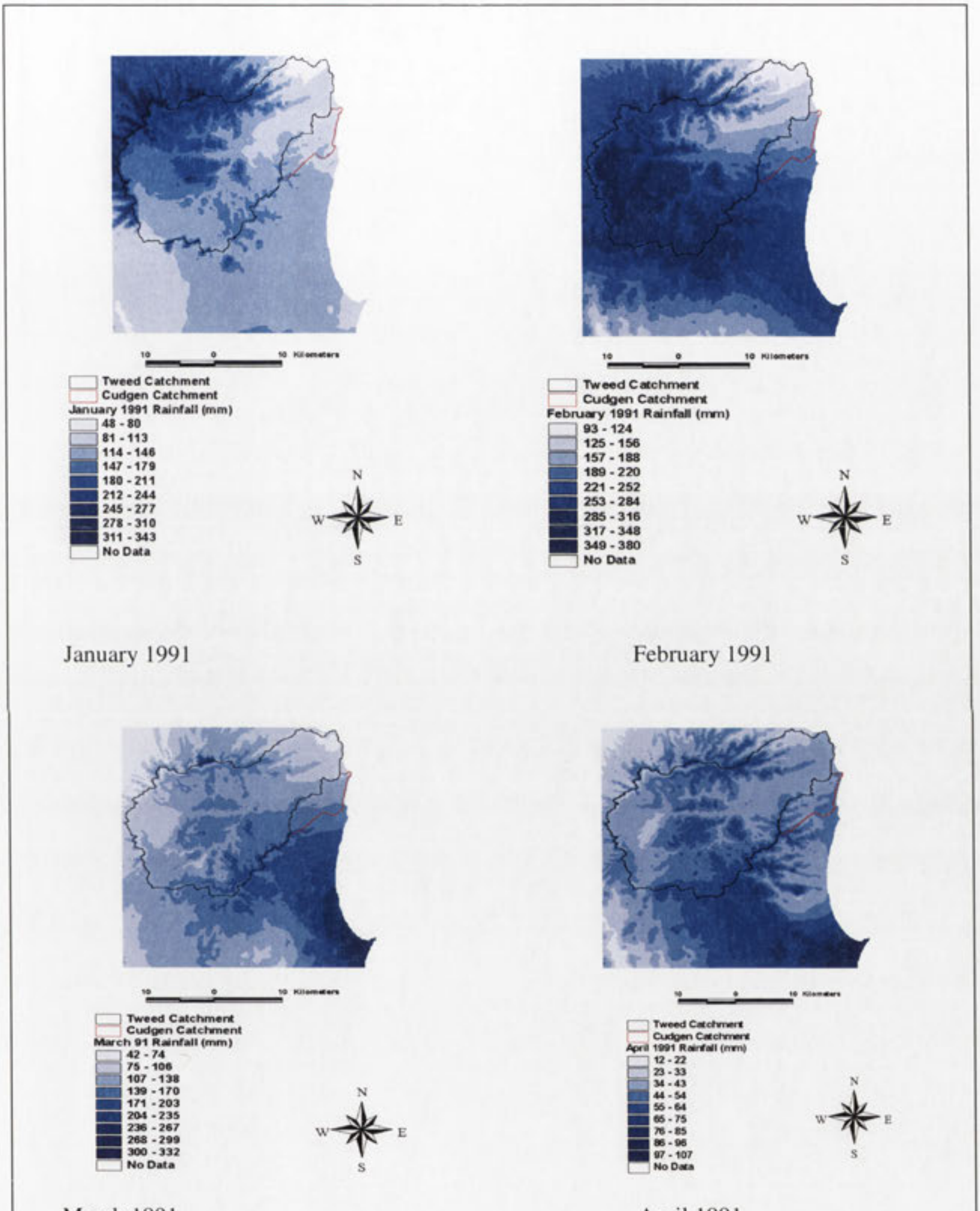


Figure 7.3 a Spatial rainfall pattern across the catchment for the months January to April 1991.

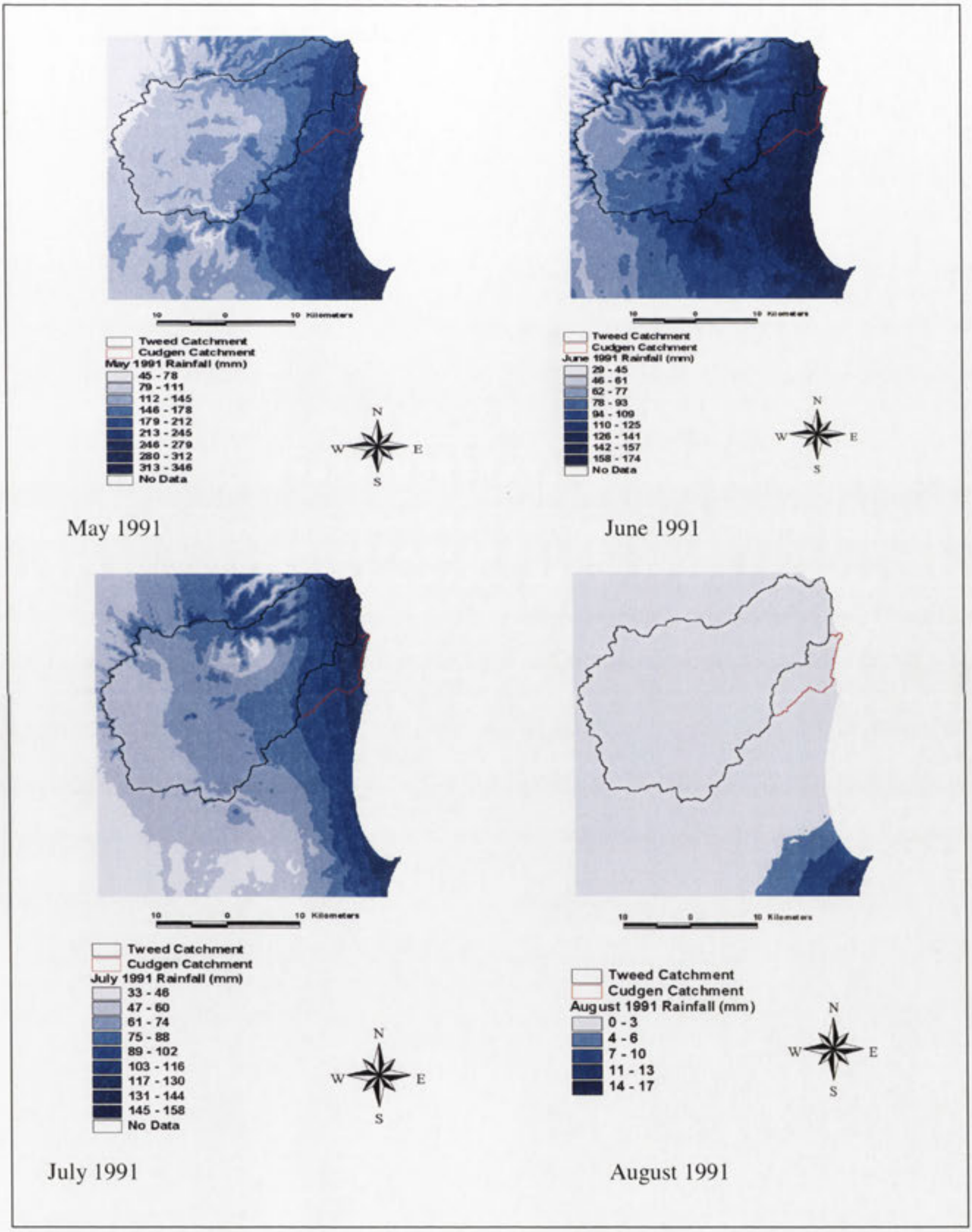


Figure 7.3 b Spatial rainfall pattern across the catchment for the months June to August 1991.

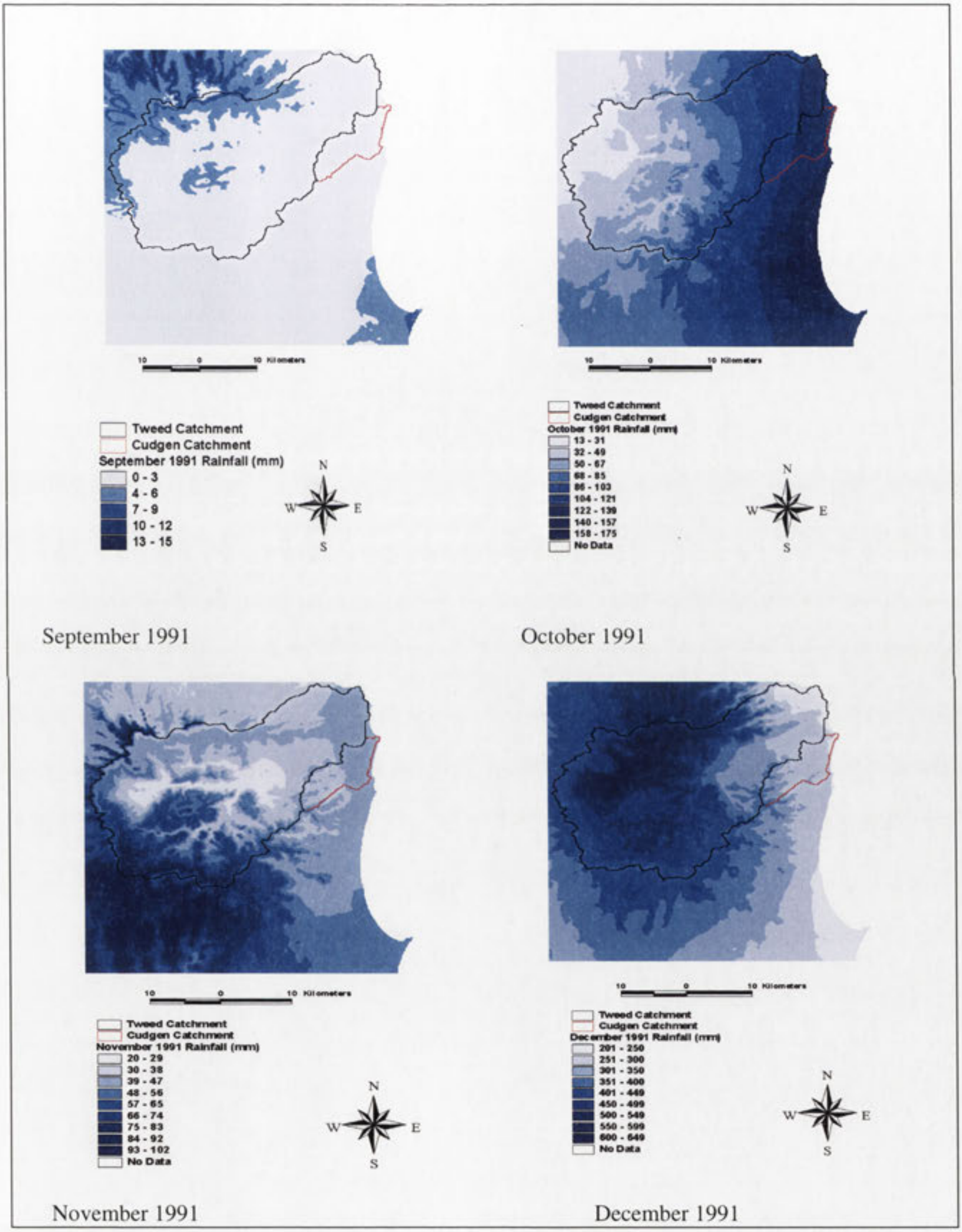


Figure 7.3 c Spatial rainfall pattern across the catchment for the months September to December 1991.

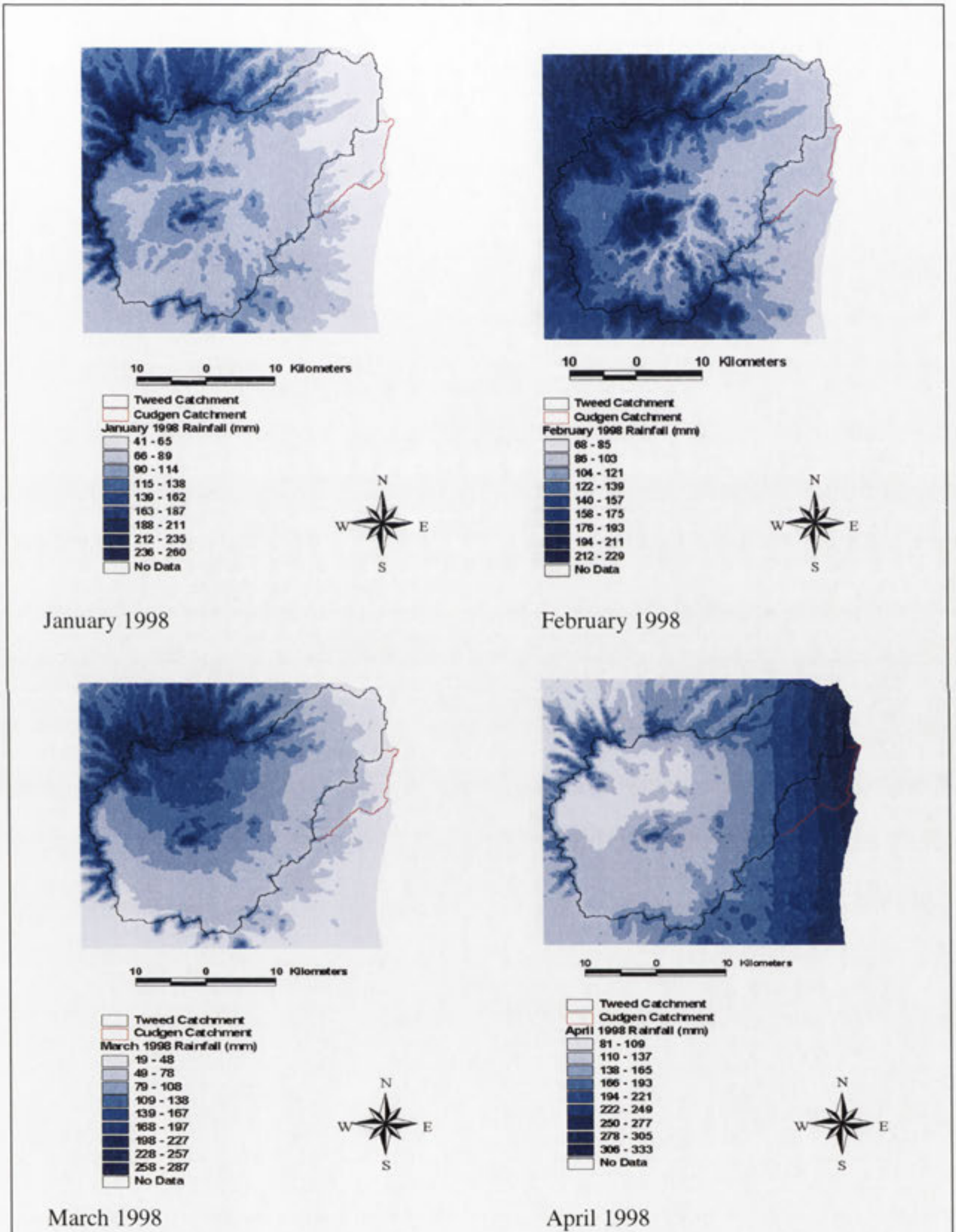


Figure 7.4 a Spatial rainfall pattern across the catchment for the months January to April 1998.

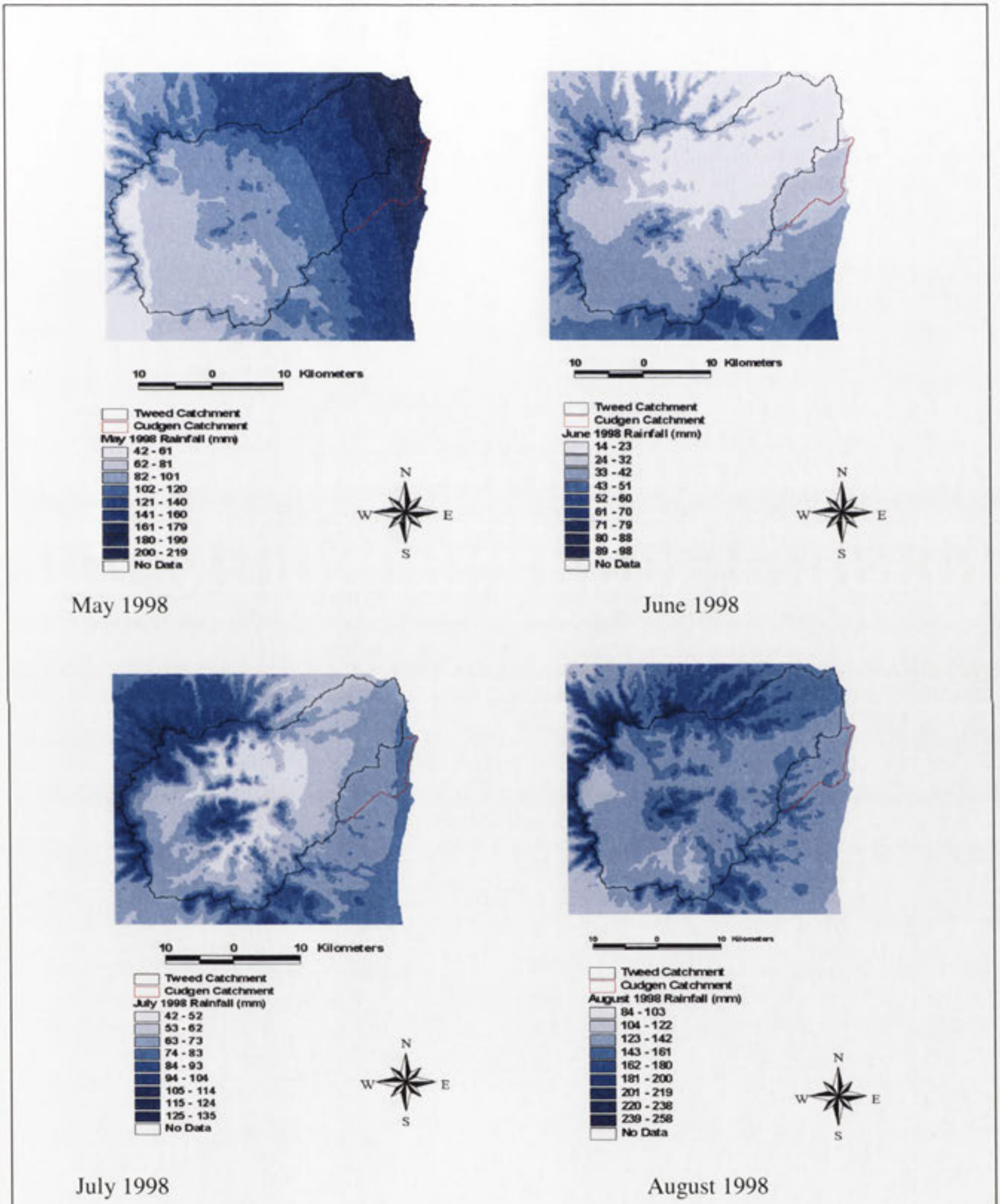


Figure 7.4 b Spatial rainfall pattern across the catchment for the months May to August 1998.

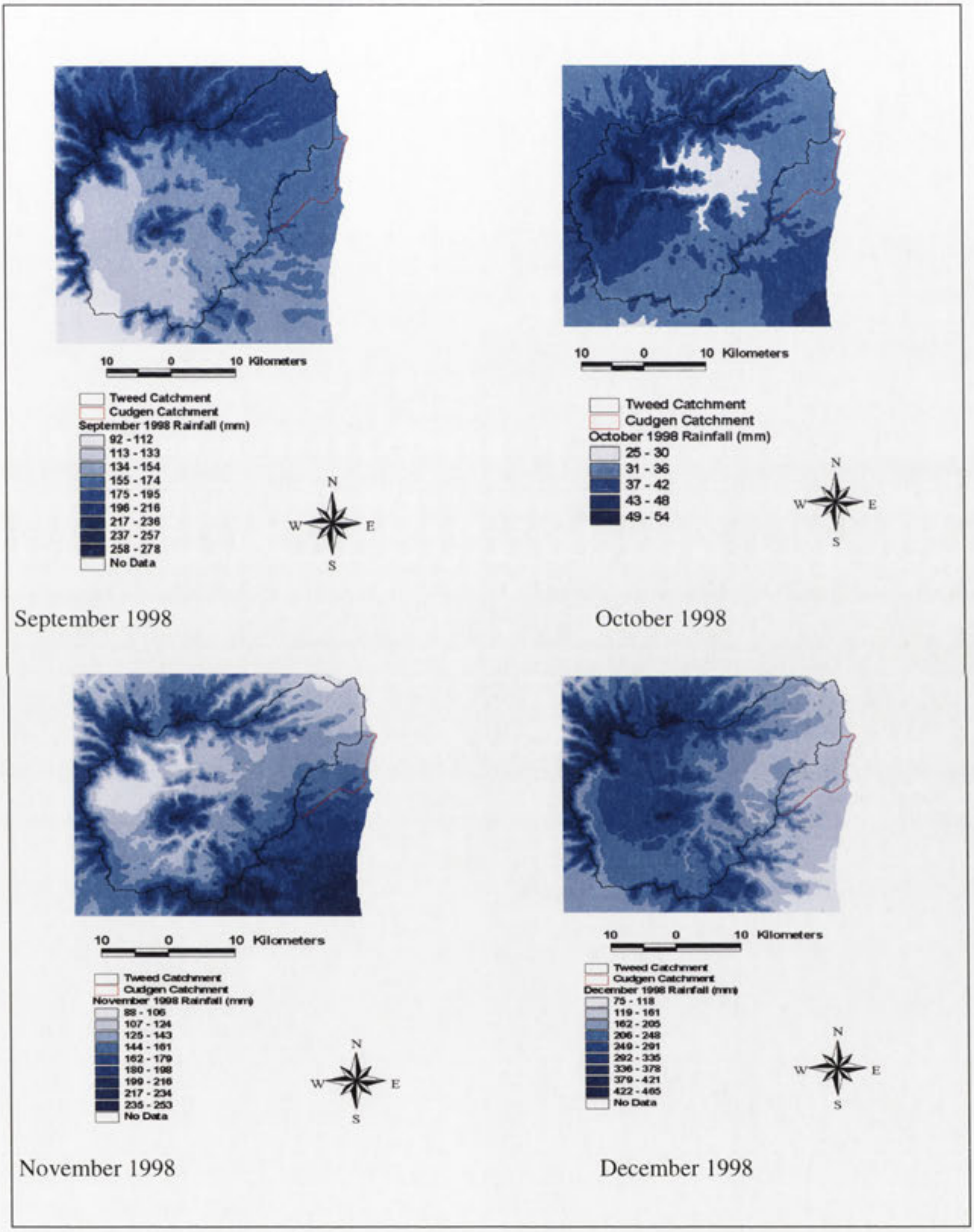


Figure 7.4 c Spatial rainfall pattern across the catchment for the months September to December 1998.

The previous rainfall surfaces presented in Chapter 4, showed seasonal variation in rainfall between the coastal regions and the upper catchment of the Tweed. This seasonal as well as spatial variation was evident in both the long-term (1921-1995) and short-term (1967-1998) spatial rainfall results. However, the monthly climate surfaces produced for even shorter time scales (i.e., for the individual years 1985, 1986, 1987, 1990, 1991, 1997 and 1998) showed even more apparent seasonal variation in the spatial rainfall pattern, from month to month. Rainfall can display variable spatial patterns when measured on short-term time scales (Hutchinson, 1989). The spatial rainfall distribution displayed by the rainfall surface maps for the years 1991 (Figure 7.3 a-c) and 1998 (Figure 7.4 a-c) show a distinct spatial pattern. The rainfall surface maps for December, January and February 1991 (Figure 7.3 a and c) and 1998 (Figure 7.4 a and c) showed that higher rainfall predominantly occurred in the upper catchment of the Tweed with higher falls confined mainly to the ranges and Mount Warning. During the autumn and winter months, from April to August, this pattern is reversed with higher rainfall predominantly confined to the coastal and floodplain regions (Figures 7.3 b and 7.4 b). The rainfall surface maps for 1985, 1986 and 1987 (Appendix C) revealed striking similarities to the other years displayed here (i.e., 1991, 1998)

In terms of the acidification of surface waters by acid sulfate soil drainage, this seasonal distribution in rainfall becomes a critical factor for small catchments that are in close proximity to the sea, especially if conditions are drier than normal during the summer months and there is a strong coastal rainfall influence during the autumn and winter months. Given the fact that acid production rates take place at higher temperatures, a period of continuously heavy, coastal rainfall, following a dry summer, would effectively raise watertable levels in small coastal catchments very quickly and mobilise acid reserves accumulated during the dry, hot summer months. The Cudgen Catchment is a relatively small catchment and because of its proximity to the sea, it is clearly under the influence of the type of rainfall patterns displayed here.

The mean spatial rainfall trends for all years were compared with the average long-term mean spatial rainfall. The mean spatial rainfall trend for the Cudgen and Tweed

Catchments for the years 1990 and 1991 is shown in Figures 7.5 and 7.6 respectively. For the period June 1990 to the first recorded fish kill during May 1991 (Figure 7.5), the spatially averaged rainfall results for the Cudgen Catchment revealed that the spatially averaged rainfall for this period was below average (See Figure 7.5), especially during the summer and early autumn. The spatially averaged rainfall results for February 1991 showed that the rainfall in the Tweed Catchment was close to the average for this particular month. The only substantial difference in the rainfall trend between the Cudgen and Tweed occurred during May 1991, when the Cudgen received significantly higher rainfall (Figure 7.3). For the Tweed, the dry trend continued right up until December 1991 when well above average rainfall fell across both catchments. Further fish kills were reported in both catchments during mid-December with pH readings dropping to levels toxic to gilled organisms (Easton, 1991). Following a period of heavy rainfall recorded across both catchments on the 11th and 12th of December 1991, it was noted that acidification of the drainage and river systems had taken place much more quickly in the Cudgen, than in the Tweed (Easton, 1991). This suggests that the Cudgen drainage system had significant acid surface water reserves prior to the December rainfall events, or that rain fell mainly on the Cudgen floodplain. These reserves had probably formed from the mobilisation of acid from within the soil profile from the previous monthly rainfall events. Further rainfall events which occurred during December simply allowed for the continued discharge of highly acidic surface waters into the lake environment. It would appear that the residual acidity in the Tweed drainage system was quickly diluted and that subsequent rainfall events during December resulted in the mobilisation of acid reserves within the soil profile at a later stage.

The rainfall surface maps provide a reasonable explanation for the difference in the amount of rainfall between the two catchments during May, June and July of 1991 (Figure 7.3 b). The spatial rainfall surface maps for these months clearly show a prevailing easterly rainfall pattern. Because of its geographical position, the Cudgen would have received the brunt of this prevailing weather pattern - resulting in significantly higher rainfall for this period - whereas inland regions of the upper Tweed Catchment had remained fairly dry. It would appear that the prevailing weather pattern that had occurred during May was a contributing factor for the fish kills that took place towards the end of this month.

The analysis of the 1997 and 1998 spatially averaged rainfall results (Figure 7.7) also produced a similar rainfall trend to the 1990-91 period. The most notable feature for this period was the very dry summer leading up to a period of above average rainfall during the months of April and May. The rainfall results for the Cudgen for these months were not reflected in those for the Tweed Catchment for the same period. The Tweed Catchment received slightly higher rainfall during the summer months with readings close to average for this time of the year. The spatial maps showed significantly higher rainfall in the upper Tweed Catchment during January, February, and March 1998 (Figure 7.4a).

Despite above average rainfall during April 1998 there were no reports of fish kills. Both catchments received rainfall well above the average for the months of August and September 1998, with a fish kill event recorded for the month of August in Cudgen Lake. As we already know from the water quality results presented in Chapter 4, the April rainfall events had little impact on reducing pH levels in Cudgen Lake whereas in August the pH levels in the lake fell quite suddenly. The rainfall results (Figure 7.7) clearly show that there was a 'lag phase' between the first month of above average rainfall, which was the month of April and the second month of above rainfall, which was August. It is also worth noting that a very dry summer took place prior to the April rainfall (Figure 7.7). The spatially averaged rainfall readings for January, February and March were well below the monthly averages. The results suggest, that the very dry summer had effectively lowered watertables to such an extent, that the rainfall events that followed during April had little impact on surface flows.

The spatial rainfall results for the 1987 Tweed River fish kills are shown in Figure 7.8. The rainfall trends leading up to the reported fish kills in March 1987 revealed a 12 month period of below average rainfall spanning November 1985 to November 1986. For the months February, March and April 1986, rainfall readings were well below average (Figure 7.8). Cane farmers on the Tweed reported large cracks in the ground measuring between five to ten centimetres in diameter during the summer months of

1986 (Quirk, personal communication, 2000). These physical changes to the soil environment provide ideal conditions for the diffusion of air through the soil profile resulting in an increased potential for pyrite oxidation.

Following this period of below average rainfall there was a return to wetter conditions. The rainfall for November 1986 peaked at above average, dropping off again during December, January and February 1986 before another rise during March 1987. Massive fish kills were observed in the upper two thirds of the Tweed River during March 1987 with all gilled aquatic life including bass, mullet, bream, flathead, luderick, gar, eels and crabs affected by the acid waters following a couple of days of very heavy rainfall (Easton, 1989). A post- mortem study of affected fish revealed obvious signs of gill damage and possible death by asphyxiation (Easton, 1989).

The analysis of the monthly spatial rainfall data for all these fish kill events indicates that there is a common climatic phenomenon that takes place prior to an event. The most notable feature common to all of these events was the period of low or below average rainfall which took place during the summer months preceded by a period of above average rainfall. These results are fairly consistent with previous observations which link fish kills with extreme climatic events (Brown *et al.*, 1983; Callinan *et al.*,1993; Sammut *et al.*, 1996). Despite this, the results shown here, do not provide any clear picture of the extent of rainfall variability that would be required for predicting the timing of a fish kill event.

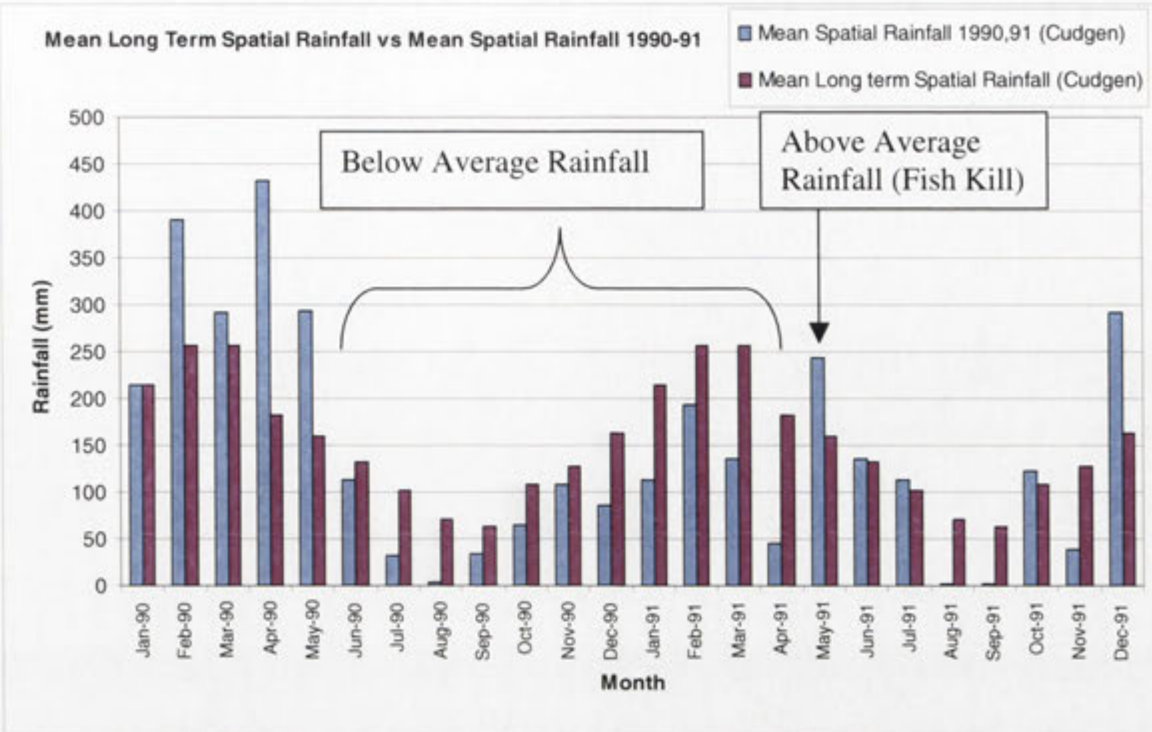


Figure 7.5 Monthly mean spatial rainfall (long-term vs 1990,91) for the Cudgen.

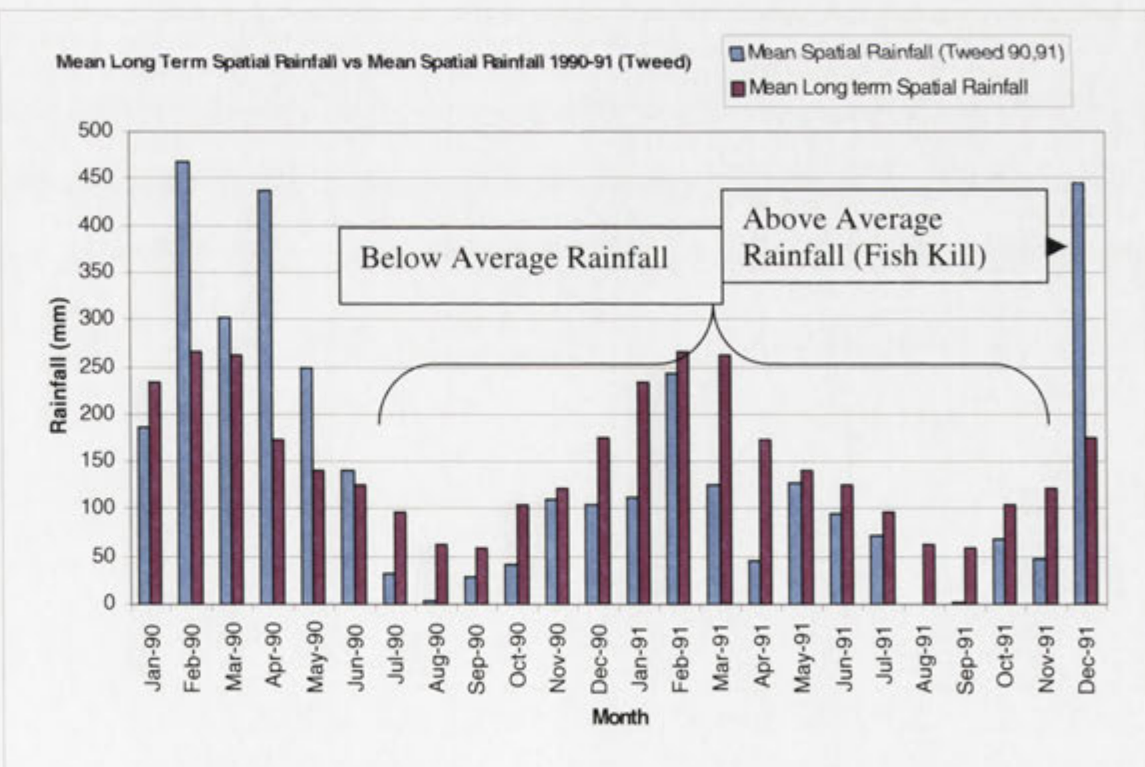


Figure 7.6 Monthly mean spatial rainfall (long-term vs 1990,91) for the Tweed.

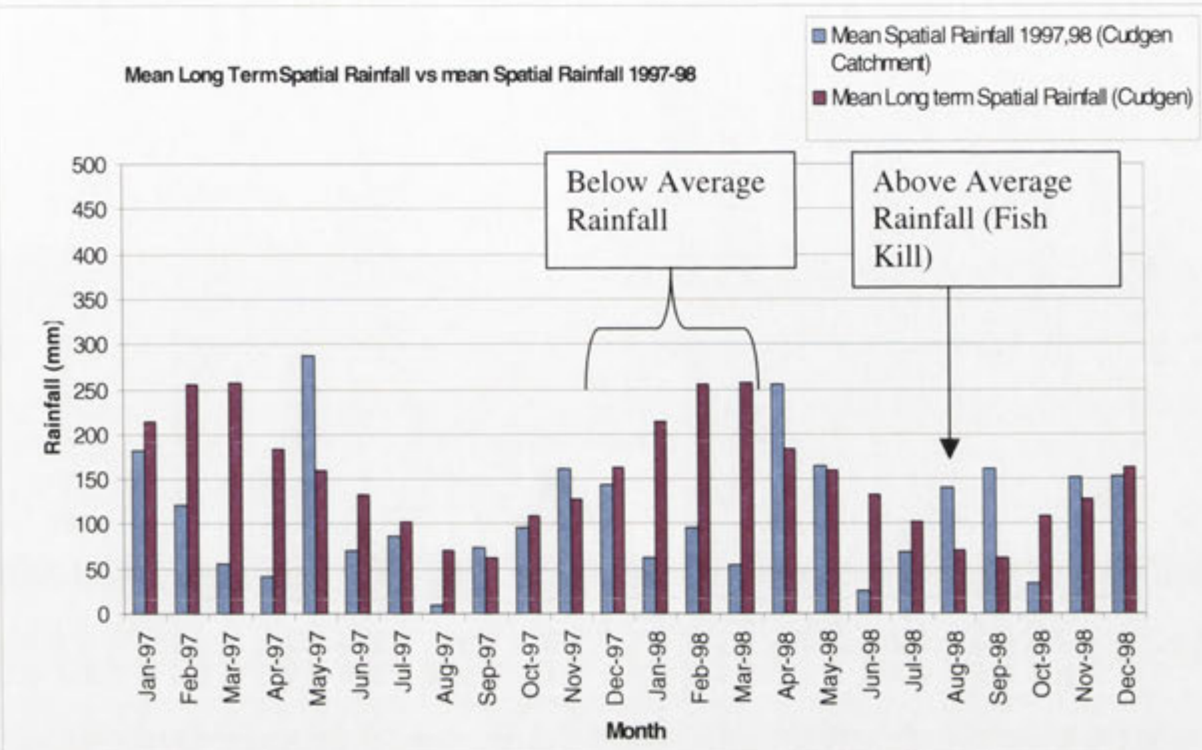


Figure 7.7 Monthly mean spatial rainfall (long-term vs 1997,98) for the Cudgen.

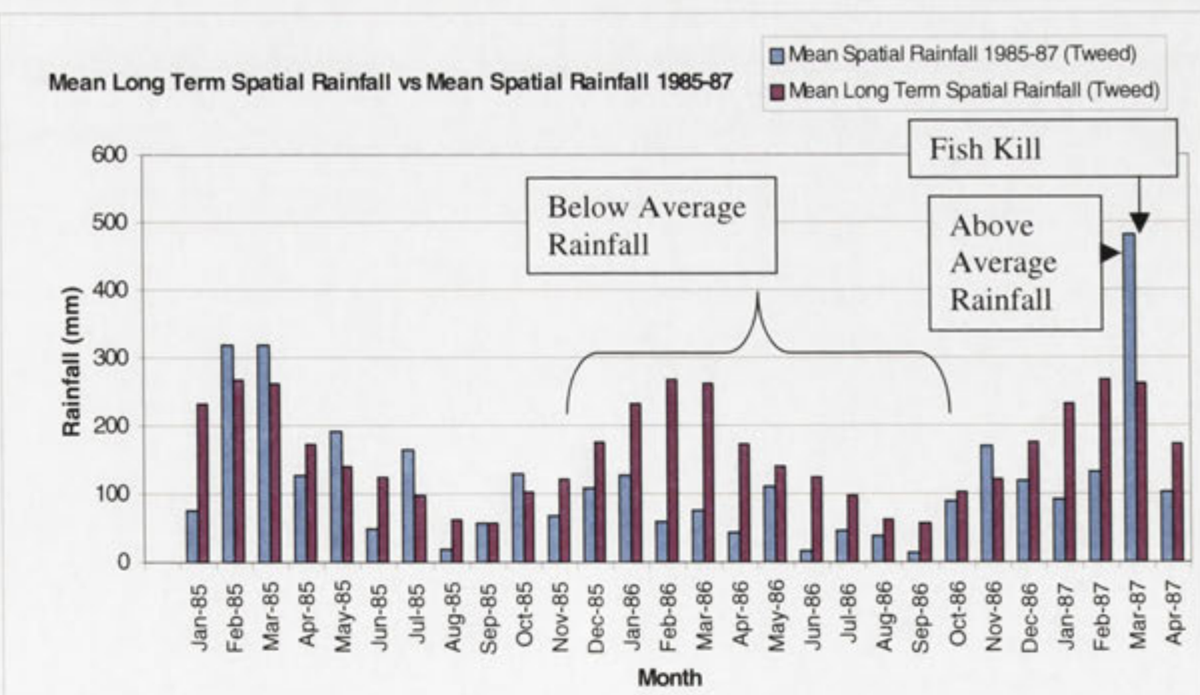


Figure 7.8 Monthly mean spatial rainfall (long-term vs 1985,87) for the Tweed. .

7.4 Using Climate Data to Model Changes to Groundwater Levels

The analysis of the spatial rainfall data for the years in which a fish kill occurred showed that there was a similar climatic pattern. This pattern suggests that the severity of a dry spell and the quantity of rainfall during or following a dry spell are pre-requisites for acid export and a fish kill occurrence. The position of the watertable during these events is also clearly important. In the Tweed, watertable levels are very low during these dry periods prior to the onset of good rainfall (Wilson *et al.,* 1999). There has been no monitoring of watertable levels in the Cudgen Catchment. Watertable monitoring conducted at the neighbouring McLeods Creek floodplain in the Tweed has shown that fluctuations in watertable levels and acid discharge events are directly related to rainfall (Wilson *et al.*, 1999). In addition, previous studies have also shown that the extent of oxidation in pyrite soils is dependent on the balance between the amount of water lost to the atmosphere through evaporation and rainfall (White *et al.*, 1997). Watertable levels in the Tweed can fall to a level of 1.8 metres, below the level of most drains, due to evapotranspiration by deep rooted crops like sugar cane (Wilson, 1995; White *et al.*, 1997). In the clay soils in these floodplains the depth of the watertable is influenced by evapotranspiration and not by the height of the water in the drains (White *et al.*, 1997; Lin *et al.*, 1995; Wilson, 1995). However, in regions such as the Shoalhaven, where shallow rooted crops are grown on highly permeable soil, the drainage network can determine watertable levels, as long as the drainage depth is below the sulfidic layer, usually around three metres (Pease, 1995).

Using mean spatial rainfall data and actual evaporation data, it is possible to model watertable levels. A simple water balance calculation was carried out using monthly rainfall and potential evaporation data. The potential evaporation data were derived from the monthly pan evaporation using the methodology discussed in section 5.3.6.2, Chapter 5, p140-141. A pan coefficient of 0.75 was used to estimate monthly potential evaporation from monthly pan evaporation. The Australian Water Research Council recommends a pan coefficient of around 0.7 ± 0.1 (Grayson *et al.*, 1996). Groundwater evaporation is usually related to potential evaporation (Ep) which refers to the rate of evapotranspiration from a well watered short grass in the same climatic conditions (Brutsaert, 1982). It has been proposed that in coastal regions where the air humidity is generally high, actual evapotranspiration is equal to potential evaporation (See White *et al.,* 1997).

The water balance is determined from the difference between the monthly rainfall and evaporation and provides an estimation of the watertable dynamics during dry and wet periods. If evaporation is higher than rainfall, there is a greater demand placed on the water storage capacity of the soil, resulting in a lowering of the watertable level. When rainfall exceeds evaporation, there is a water surplus and watertable levels rise. A water balance measures the loss of water from the soil and is only an estimate of watertable levels.

Figures 7.9 to 7.12 illustrate the water balance for certain years when a recorded fish kill event took place. The results clearly show some striking similarities between events. First, there is the characteristic period, during which there is watertable deficit for the warmer months of spring and summer. Following this deficit there is a return to surplus rainfall; however, despite the good rainfall and a watertable surplus, no fish kill events were observed for this first month. Secondly, prior to each fish kill event, there is a distinct 'lag phase' in which there is a decline in the surplus rainfall following this first month, proceeded then by a gradual increase in the surplus rainfall. The results suggest that both watertable height and season factors are responsible for the timing of a fish kill event.

A cumulative excess rainfall calculation (Figure 7.13) was also carried out to determine the amount of excess rainfall required for the translocation of acid from the soil environment to the aquatic ecosystem. The similarity in the trends presented in Figure 7.13, provides some indication of the amount of excess rainfall required to initiate a fish kill event, when evaporation is taken into account. For both the 1991 and 1998 fish kill events, approximately 230-270 mm of excess rainfall was required to result in a fish kill. In other words, sufficient excess rainfall (~ 250 mm) is therefore required to raise watertable levels and mobilise acid reserves.

Figure 7.13 shows that the excess rainfall values are negative during the spring and summer months prior to the first significant rainfall event. Once the pH of the soil drops to below 4, oxidation of pyrite, catalysed by soil bacteria takes place rapidly. The oxidation of pyrite results in the production of Fe II which is further oxidised to Fe III resulting in the liberation of more acid. At pH less than 4, Fe III acts as the electron acceptor and the oxidation of pyrite can still occur even in the absence of oxygen (Nordstrom, 1982). Soil samples taken from the Clothiers creek floodplain have shown that the depth of Actual ASS at pH 4 is around 0.5 metres (Johnston, 1999). The oxidation of pyrite resulting from the accelerated production of Fe III by the soil bacteria *Thiobacillus .ferrooxidans*, and *Ferrobacillus ferrooxidans* is a temperature dependent process strongly influenced by oxygen and nutrient availability (Nordstrom, 1982). Various authors (Luther *et al.*, 1985; Giblin and Howarth 1984) have linked seasonal factors to dramatic changes in soil chemistry and pyrite oxidation conditions, especially during the summer months. In the case of the 1985-1986 drought, the large cracks that had developed in the ground would have exposed the soil to an abundant supply of air which would have also infiltrated deep within the soil profile. The bacterium *T ferrooxidans* is able to produce considerable quantities of ferric iron when oxygen is in abundant supply. In addition, the production of ferric iron (Fe III) greatly increases the oxidation rate of pyrite (Garrels and Thompson, 1960). Therefore, low rainfall, higher temperatures and a large watertable deficit during late spring and summer, would have created ideal conditions for pyrite oxidation.

For the 1998 fish kill event, the water quality results revealed a dramatic change in drain water chemistry during the first month of rainfall, following the dry summer with little change in the lake water quality at depth. A drop in monthly rainfall and an increase in the water balance deficit, occurred during the characteristic 'lag phase'. The fact that there was a dramatic and almost immediate change in water chemistry following the 'lag phase' and coinciding with the rainfall events in August, suggests that a large proportion of the leachable acidity was moved from the soil and translocated to the soil surface, during and following the first month of heavy rainfall. Since the soil would have been fairly saturated during the characteristic 'lag phase', it is possible that some additional oxidation of pyrite would have taken place from the reaction involving Fe^{3+} with FeS_2 (White *et al.,* 1997). Any additional acidity produced during this period would have continued to slowly leach into the drainage system with further rainfall events. Finally, the brief dry spell that followed the first month of heavy rainfall would have also resulted in the evaporation of some surface water, thus resulting in an increase in the concentration of surface water acidity. Such concentrations could well have been in the order of those previously modelled in Chapters 4 and 5.

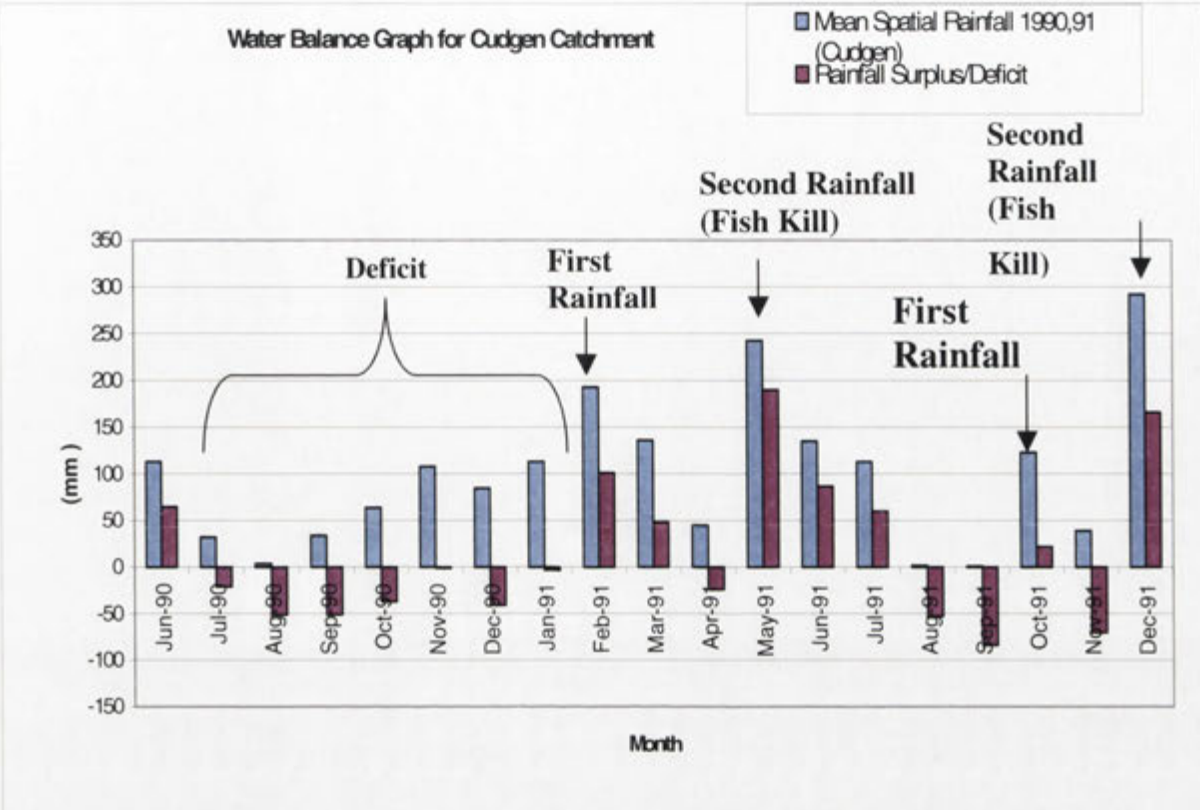


Figure 7.9 Water balance for Cudgen Catchment 1990-1991.

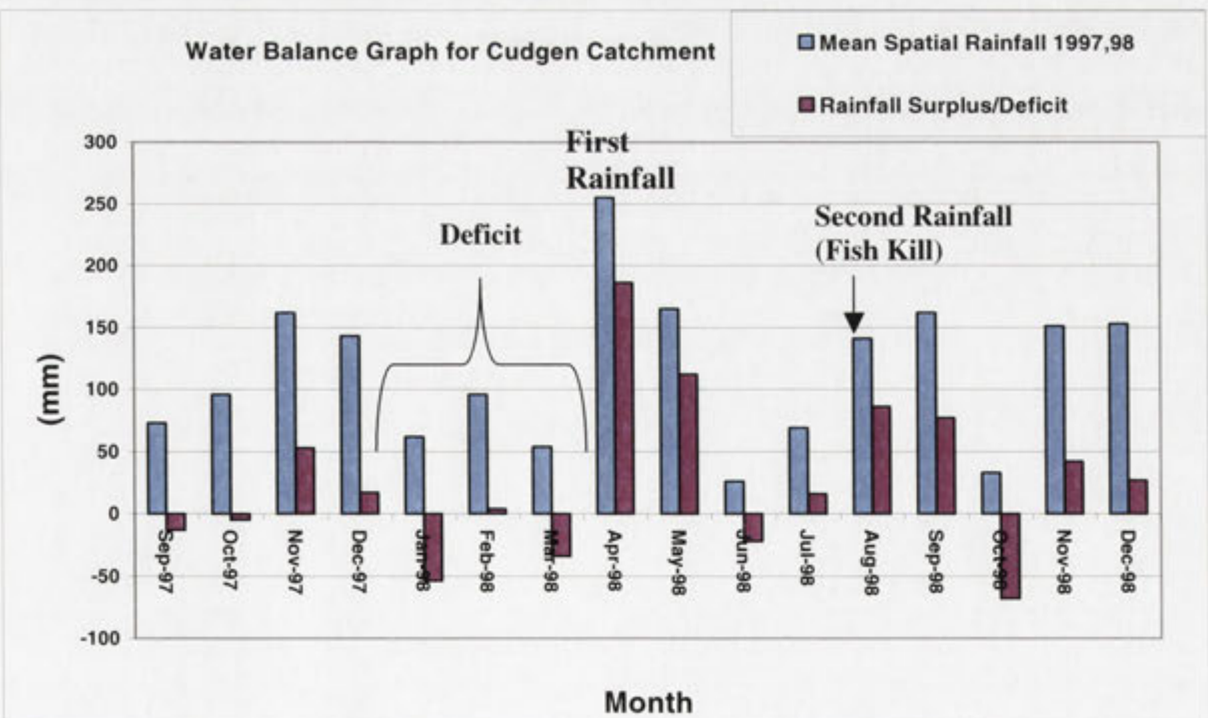


Figure 7.10 Water balance for the Cudgen Catchment 1997-1998.

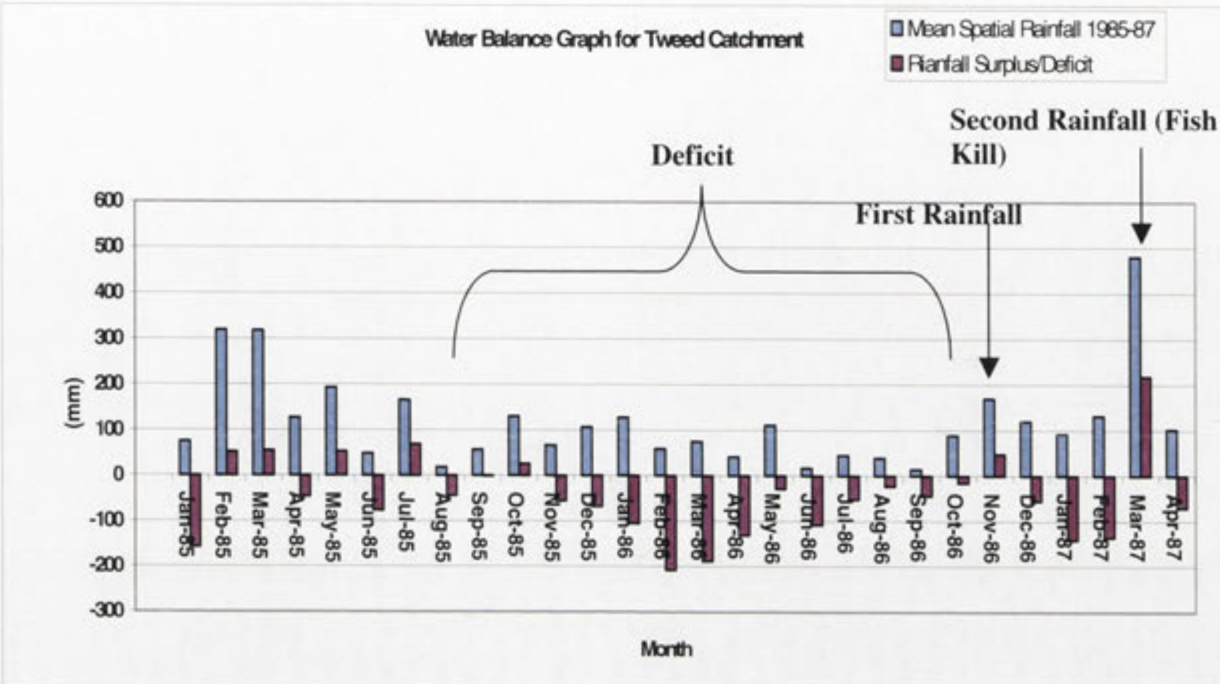


Figure 7.11 Water balance for the Tweed Catchment 1985-1987.

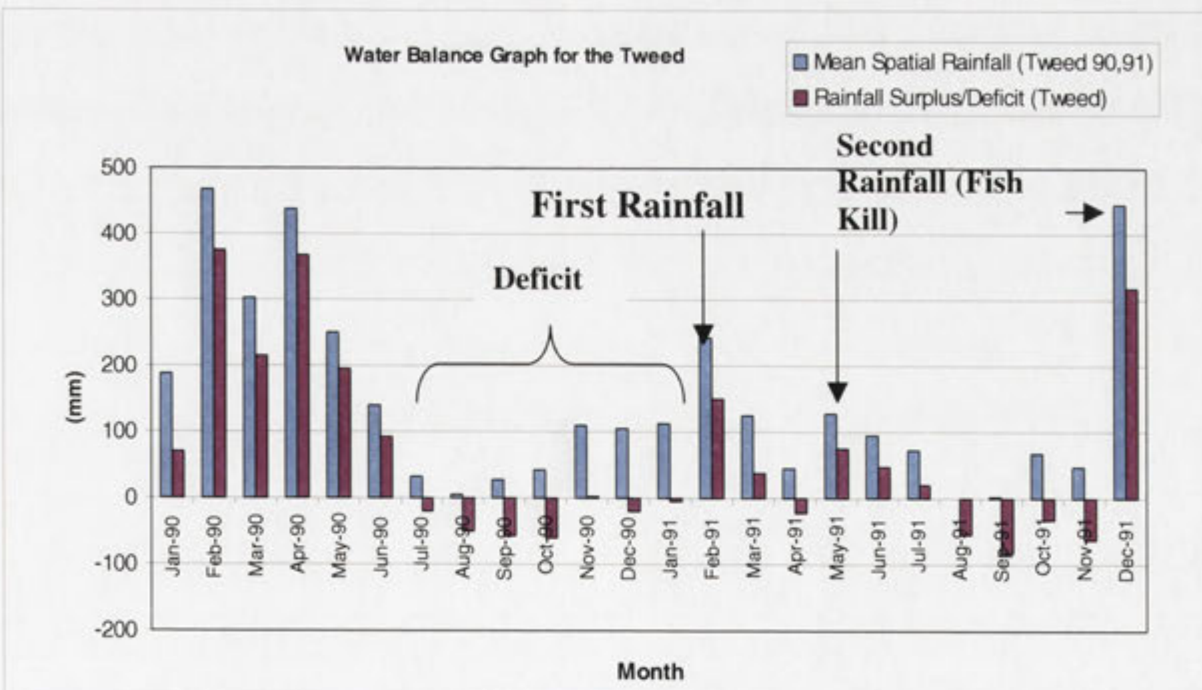
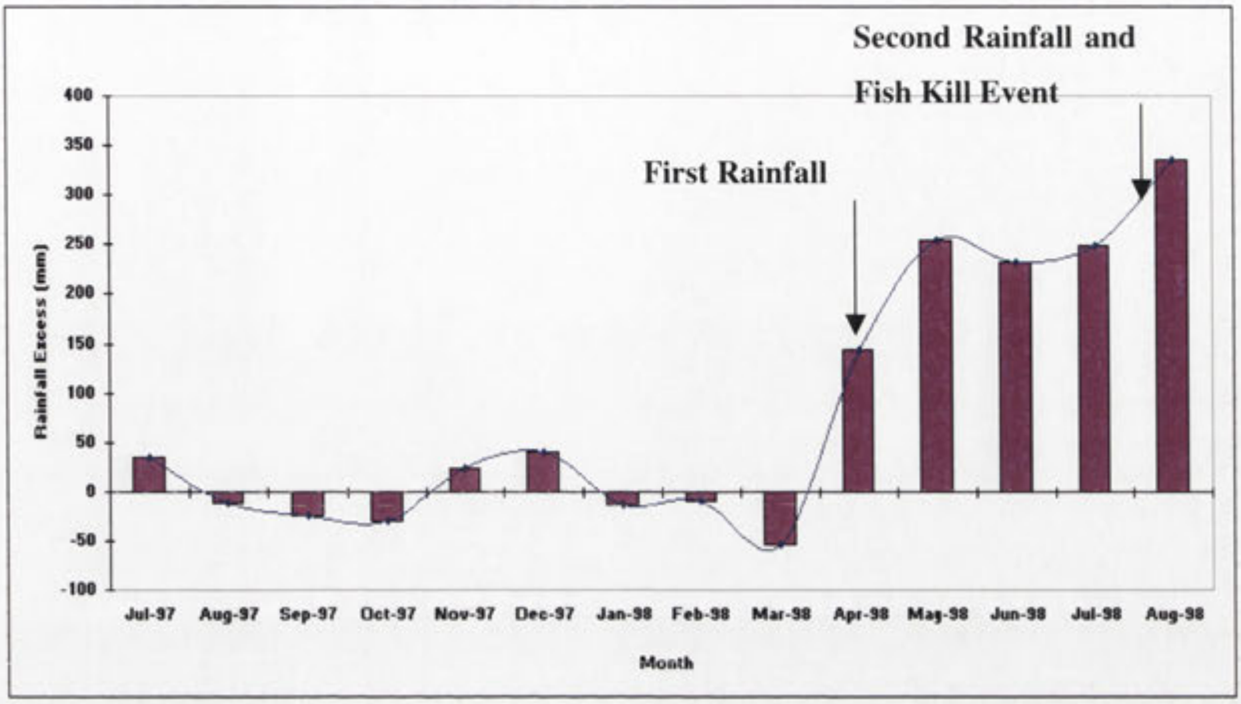


Figure 7.12 Water balance for the Tweed Catchment 1990-1991.

(a)



(b)

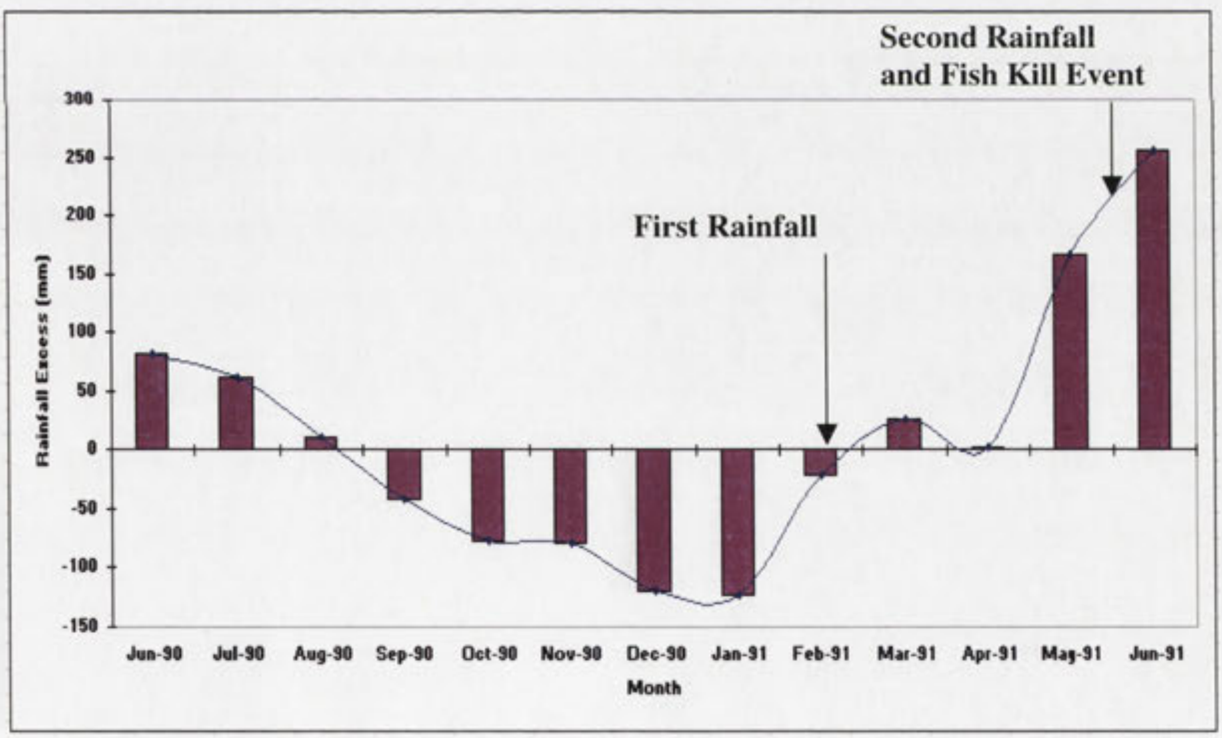


Figure 7.13 Cumulative rainfall excess for the period July 1997-August 1998 (a) and for the period June 1990-June 1991 (b).

7.5 Relationship Between Streamflow and Acid Discharge

The relationship between acid discharge and streamflow events, for the period leading up to the first fish kills, was examined for both fish kill events (1991 and 1998) in the Cudgen. The streamflow for these periods was modelled using the monthly mean spatial rainfall for each month and the runoff coefficient derived from the linear regression equation calculated in section 4.2.7, Chapter 4, p77-83. Runoff and flow accumulation grids were derived from the monthly rainfall grids, to estimate the total accumulated flows for each month. The maximum and minimum pH values for the lake and drain water were compared against the streamflow for the same period. The relationship between streamflow and pH for 1998 and 1991 is summarised in Tables 7.2 and 7.3 respectively. Due to a lack of water quality data for the 1991 fish kill event, it is difficult to arrive at any conclusions concerning the relationship between streamflow and acid discharge for this period.

Table 7.2 Accumulated Flows and pH Range* for the Cudgen from March to August 1998.

Month	Modelled Flow (ML)	pH Lake*	pH Drain (T2 (Main Drain)
March 98	**4,316**	**7.0-7.2**	**6.0-7.8**
April 98	**38,687**	**5.0-7.2**	**3.5-4.0**
May 98	**19,155**	**5.0- 6.0**	**3.5-4.0**
June 98	**1,648**	**5.0-6.5**	**3.3-3.3**
July 98	**5,404**	**6.2-6.7**	**3.0-4.0**
August 98 #	**18,467**	**4.3-4.6**	**2.8-4.0**

pH range based on pH results obtained at depth and surface
 # Fish kill event
(The total accumulated flow for the period April to August 1998 is 83,361 ML)

Flow regimes varied significantly in the lead-up to both fish kill events. For the 1998 fish kills, the modelled large surface water flows for April and May had little impact on reducing the pH levels in the lake, despite the low pH levels recorded in the drainage water. The reason for this is not exactly clear, however, it would appear that either there was a dilution effect from the initial surface water flow or there was a considerable amount of leachable acidity, which had not reached the surface waters. Watertable levels were low prior to the April rainfall and therefore, the initial rainfall period probably resulted in little or no runoff depending on the intensity of the rainfall during this period. Heavy rainfall on the other hand, would have resulted in mostly runoff with very little surface water acidity in the first flush.

It is interesting to note that the spatial distribution of rainfall for this period showed a strong coastal rainfall influence for these two months with heavier falls occurring on the coastal fringe of the catchment and less rainfall in the upper catchment (Figure 7.14 a). This would have meant that a considerable amount of non-acidified water might have originated from the surrounding foreshore of the lake and the township of Bogangar. The modelling results presented in Chapter 5 (section 5.3.7, p144), showed that on average, around 20 percent of the surface water that enters the lake originates from this region. Under these climatic conditions, the amount of freshwater surface flow could be higher than 20 percent. This climatic pattern is in direct contrast to the pattern observed for August which showed higher rainfall occurring in the upper part of the catchment (Figure 7.14 b). This would effectively translate into higher flows originating up-stream from the lake.

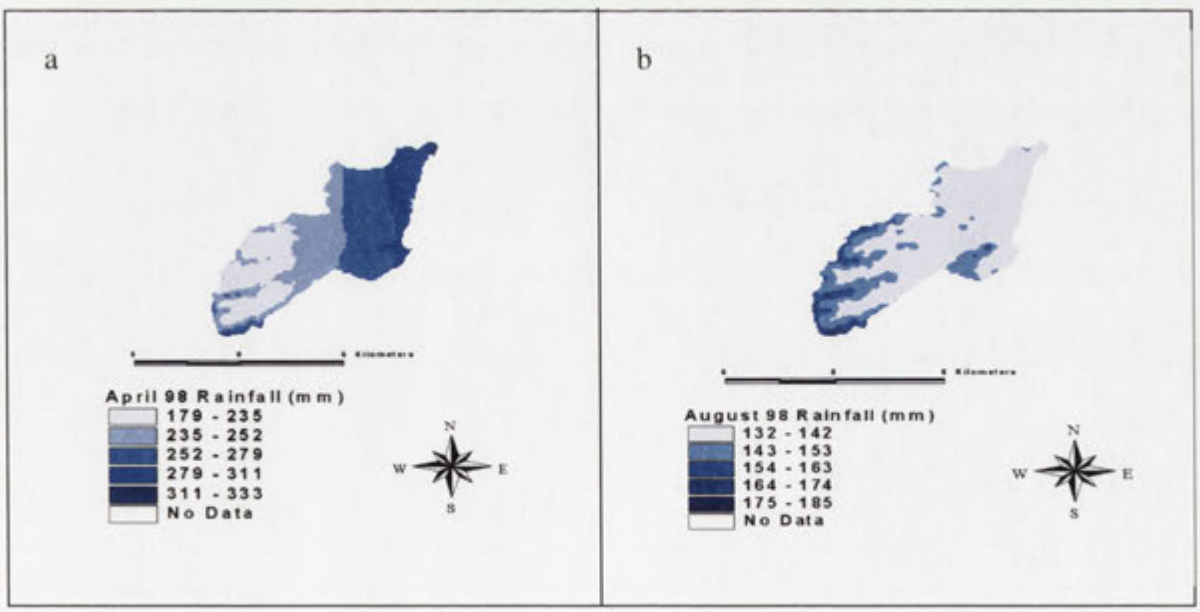


Figure 7.14 Different spatial rainfall patterns for April (a) and August (b) 1998.

The low flows which followed April and May also had little or no impact on reducing pH levels in the lake even though pH remained low (pH 3.3-4.0) in the drains. At some locations within the drainage network the pH continued to drop to below pH 3. The estimated monthly flow following this period increased from 5,404 ML for the month of July to over 18,000 ML for August. The average monthly surface water flow of 18,467 ML for August was sufficient to displace acidic drain waters and reduce the pH levels in the lake from 6.2 to 4.3. Most aquatic life including all the fish species surveyed in the lake could not survive at this pH.

The results for the 1991 fish kill event showed that the large flow events during February and March, which followed the long dry spell, had little impact on reducing pH levels in the lake. The total accumulated flow of 31,188 ML for May reduced pH levels in the lake from 6.0 to 4.3. Due to the lack of water quality data for this period, it is difficult to make any real conclusions regarding flows and their impact on water chemistry and fish kills. However, it would appear that there is a similar trend for both fish kill events. It is important to also note that the total accumulated flows for each month leading up to the first fish kill event for the years 1991 and 1998, were 84,713 ML and 83,361 ML respectively. This is consistent with the results presented in section 7.4 which suggest that a certain quantity of the total accumulated surface water flow is required before there is any real change in lake water quality.

Table 7.3 Accumulated flows and pH range for the Cudgen from January to May 1991.

Month	Modelled Flow (ML)	pH Lake*	pH Drain (T2 Main Drain)
January	**11,148**	**6.0-6.6**	**ND**
February	**27,848**	**6.0**	**2.7-3.3**
March	**23,380**	**ND**	**ND**
April	**2,297**	**ND**	**ND**
May #	**31,188**	**4.3**	**3.3**

** Readings taken at Cudgen Lake resort ND: No data available*
 # Fish kill event (The total accumulated flow for the period February to May 1991 is 84,713 ML).

For both periods leading up to the major fish kill events there was a distinct period of low surface water flow (< 5,404 ML) which coincided with the characteristic 'lag phase' referred to in section 7.4. This period of low rainfall and low surface flows provides opportunistic conditions for the further acidification of surface waters. In conclusion, the results here clearly suggest that there is an optimum flow rate that is reached before there is any real change in the lake water chemistry. Although the tidal exchange between the sea and the lake environment is small, it is obviously sufficient to effectively neutralise any acidity originating from these low surface flows. It would also appear that once the store of soil moisture reaches saturation, any subsequent runoff from rainfall events quickly becomes acidified and added to the surface water and streamflow.

Although the modelling of surface flows has provided some insight into the dynamics between flow and the acidification of the lake environment, it cannot replace regular "real-time" water quality and streamflow gauge monitoring. Clearly, the modelling does not take into account the daily or hourly rainfall and streamflow events during these time periods or even the magnitude of the rainfall events. For example, a heavy rainfall event within a short time frame would result in mostly runoff with little soil water uptake, whereas, rainfall which is constant over a longer time period would result in more uptake by the soil environment.

The results clearly show that sufficient cumulative rainfall is required before any acid in the soil is discharged to the surface and before aquatic acidification takes place. These results show that once the watertable rises to the soil surface, considerable rainfall is required before there is any significant change in the water quality of the lake. Clearly, once the acid reaches the surface water, surface flow then becomes the fundamental driver for the transportation of acid to the lake environment. The magnitude of an acid discharge could, therefore, be reduced simply through the management surface water flows.

7.6 Predicting Fish Kill Events Using Deciles and the SOI.

The rainfall results presented in the previous section suggest that a fish kill event is closely associated with periods of below average rainfall, followed by a period of above average rainfall. The results also suggest that the timing as well as the duration and severity of a dry spell might be a contributing factor.

For all the years in which a fish kill event was recorded there was a distinct dry period in which rainfall percentiles were equal or below the 30 percent extreme dry (Figure 7.15). The 12 monthly decile graphs shows that the fish kills occurred during or following an extremely dry period in which the monthly decile reading were 0.3 or lower. The graphs also show that fish kills were generally associated with a break in the dry period during which there was a return to higher rainfall.

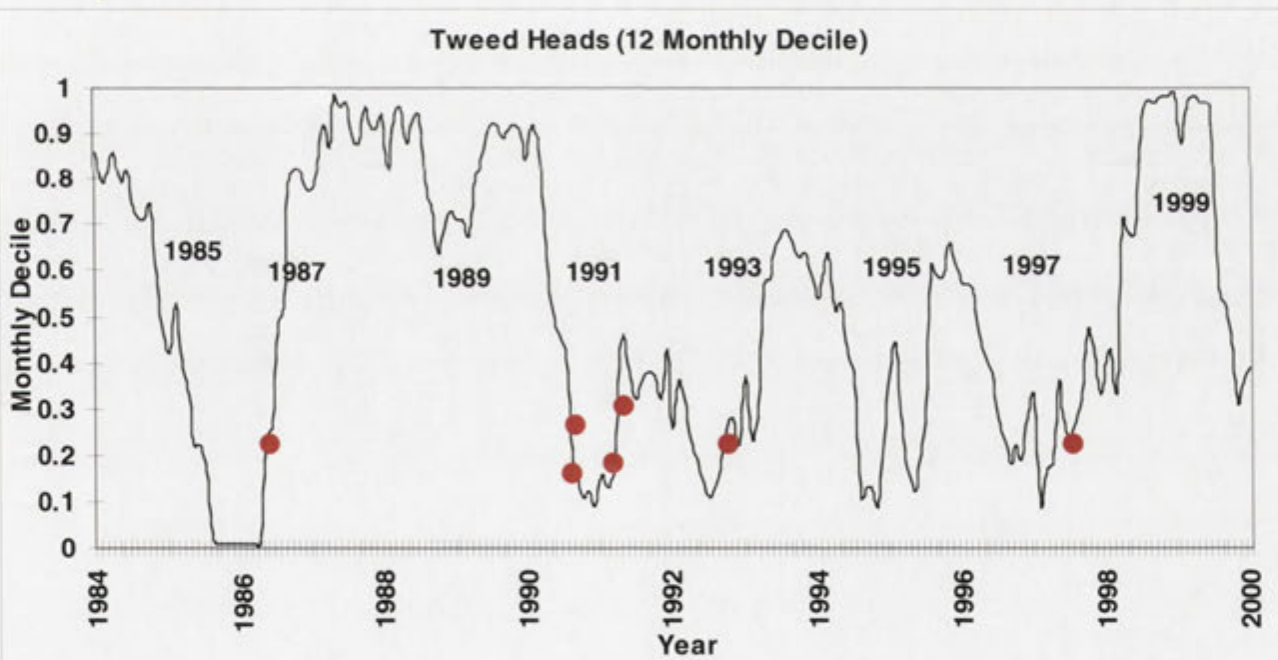
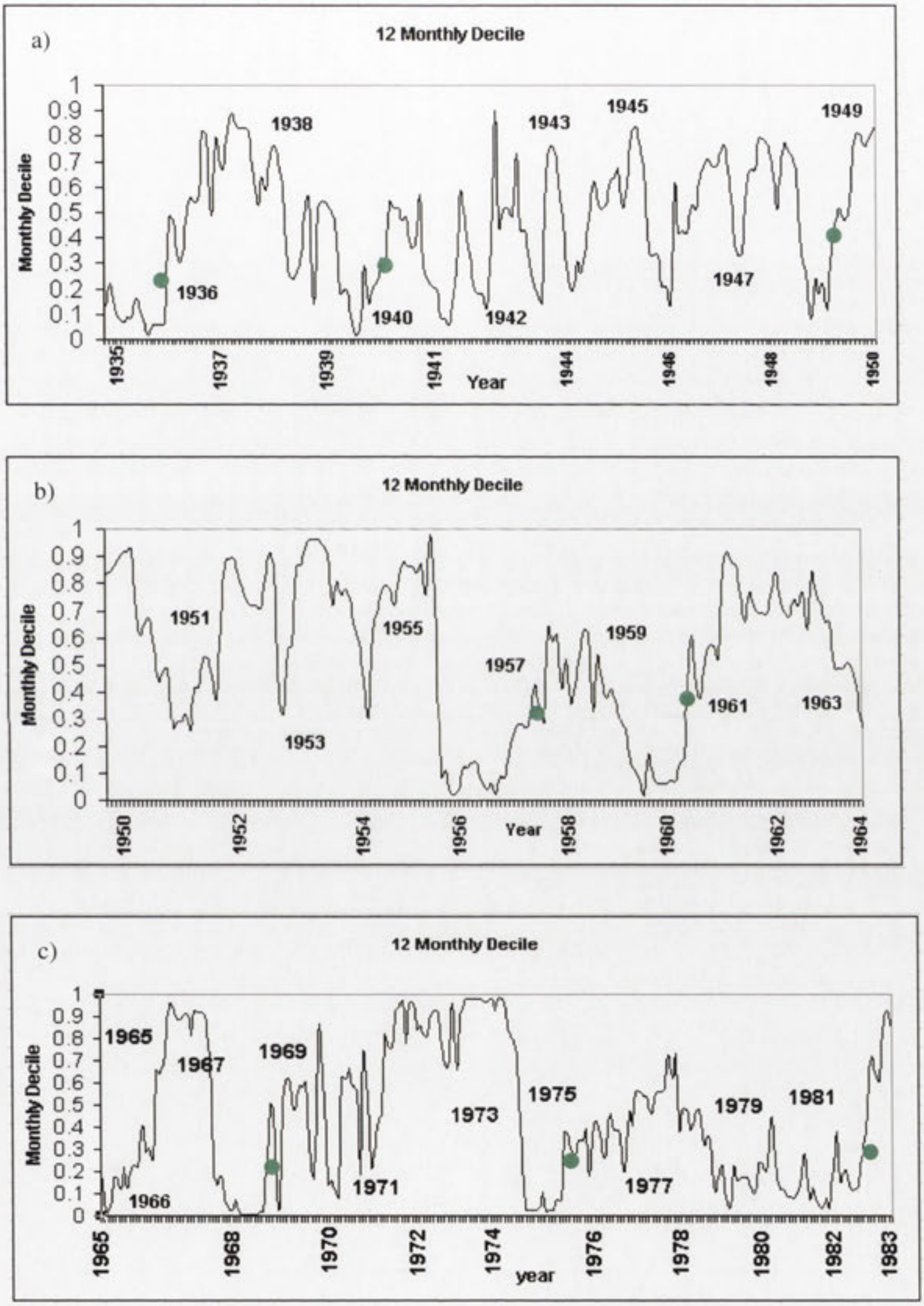


Figure 7.15 Twelve monthly rainfall decile for Murwillumbah from December 1984 to December 2000 (Red dots indicate fish kill events).

By using the 12 monthly decile method it is possible to take the historical rainfall data and determine when a fish kill event might have taken place over the last 80 years. Figures 7.16 a-c shows the 12 monthly decile readings from the period 1935 to 1983. Based on these results, we estimate that a fish kill event probably occurred at least eight times (i.e., 1935, 1940, 1949, 1957, 1961, 1969, 1975, 1982). It is interesting to note that since the late 1970s to the year 2000 there would appear to be an increase in the frequency of years that were classed as extremely dry with a decile reading less than 0.2. It is worth noting that the mid-1950's and early 1970's were periods of high rainfall. These results are a reflection of the 2D seasonality results presented in Chapter 6.



Figures 7.16 Twelve monthly deciles for the period a) 1935-1994 b) 1950-1964 c) 1965-1983 (Green dots indicate when a fish kill event may have occurred).

The frequency of El Niño events (negative SOI) and their relationships to observed fish kills is shown in Figure 7.17. This graph shows that there is strong relationship between an El Niño event and fish kills with six out of the eight kill events coinciding with an El Niño episode. The 1998 event occurred when the SOI was positive. However, 1998 event had followed a more protracted El Niño cycle than the other events. Based on these results, in conjunction with an analysis of the rainfall data, it would appear fish kills were closely associated, not just with El Niño events per se, but more specifically where there were intermittent periods of heavy rainfall which had occurred during or following an El Niño episode.

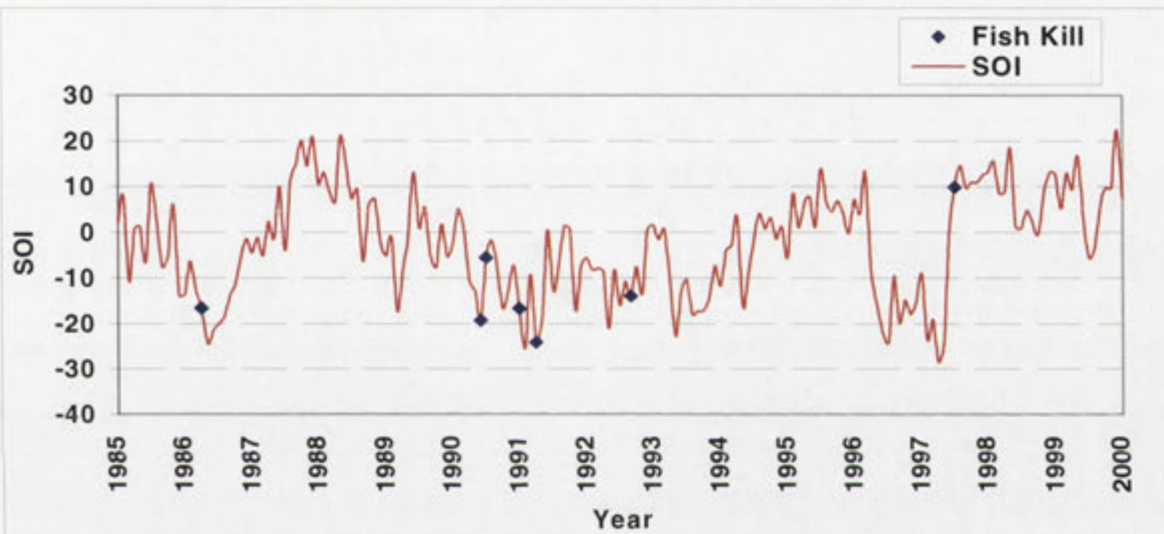


Figure 7.17 Relationship between fish kill events and SOI from the period December 1985 to December 2000.

The use of SOI and Deciles for predicting future fish kill events is an extremely crude method to say the least. Clearly, there is a need to use a more scientific method for calculating the probability of an event taking place. Despite this, we are fairly confident that based on these results, fish kill events are closely associated with heavy rainfall events that occur during long extended periods of extremely dry weather – a typical El Niño weather pattern. It should also be noted that in some cases fish kills did not occur under these conditions. For example, there were no fish kill events recorded during or around 1995. Furthermore, from observation, a fish kill event may occur in one catchment or location and not in another or that the timing of an event may differ between two locations (Easton, 1991). One of the factors determining fish kills could be the spatial distribution of rainfall in the catchment.

7.7 Predicting Fish Kills Using a Probability Tree

The previous section examined the link between climate and fish kills. It was concluded that fish kills had always occurred during a period of extremely dry conditions (often closely associated with El Niño episodes), followed by a succession of heavy, but intermittent rainfall. Similar monthly rainfall patterns were also evident prior to a fish kill event. These findings suggest that the ability to accurately predict the timing of a fish kill event could be further refined by the development of a probability model based on the time of year the event had taken place and deviation from monthly mean rainfall.

In this section the "tree" analysis (Chambers and Hastie, 1992) implemented in S-Plus (Becker *et al.,* 1988) was used to explore the probability of a fish kill event. This analysis uses a stepwise approach to identify the likelihood of an event taking place using the rainfall of the month in which the event had occurred and the previous 11 months. Rainfall records at Tweed Heads were chosen for the model, because this station had an entire record of monthly rainfall results for all fish kill events. Two tree models were developed; the first was based on the 12 monthly cumulative rainfall record for the period 1984 to 2000. A twelve month cumulative approach was chosen because it would be comparable with the 12 Decile in section 7.6. The second model was developed using only monthly rainfall records for the same period.

7.7.1 Probability Tree Using 12 Monthly Cumulative Rainfall Data

A breakdown in the probabilities of a fish kill event taking place was constructed as a probability tree (Figure 7.18) using cumulative rainfall data. For each split in the tree there is a corresponding increase in the probability of a fish kill taking place. The initial probability starts at 4% when the cumulative rainfall for the preceding 12 months is less than 1698. The statistical analysis gave a mis-classification error rate of 5 in 180 and a residual mean deviance of 0.09118 or 16 out of 175. This means that the probability tree provides a reasonably high degree of accuracy in predicting a fish kill event. The probability tree shows that for an event to occur, the cumulative rainfall for the preceding 12 months must be less than 1698mm (Figure 7.19). This amount of rainfall represents slightly less than the average spatially distributed annual rainfall of 1820mm for the Tweed Catchment and 1840mm for the Cudgen Catchment (See Figure 4.14, Chapter 4). This result supports the previous findings which suggest that these events are closely linked to periods of low rainfall.

As shown in Figure 7.18, there is a 66 % probability of an event taking place when the rainfall for the month (Mx) is greater than 243mm and if the cumulative rainfall is less than 1698mm. If the rainfall is less than 243mm and the eleventh (M11) and second (M2) month before the event is less than 72mm and 45mm respectively, there is only a 50% probability of an event taking place.

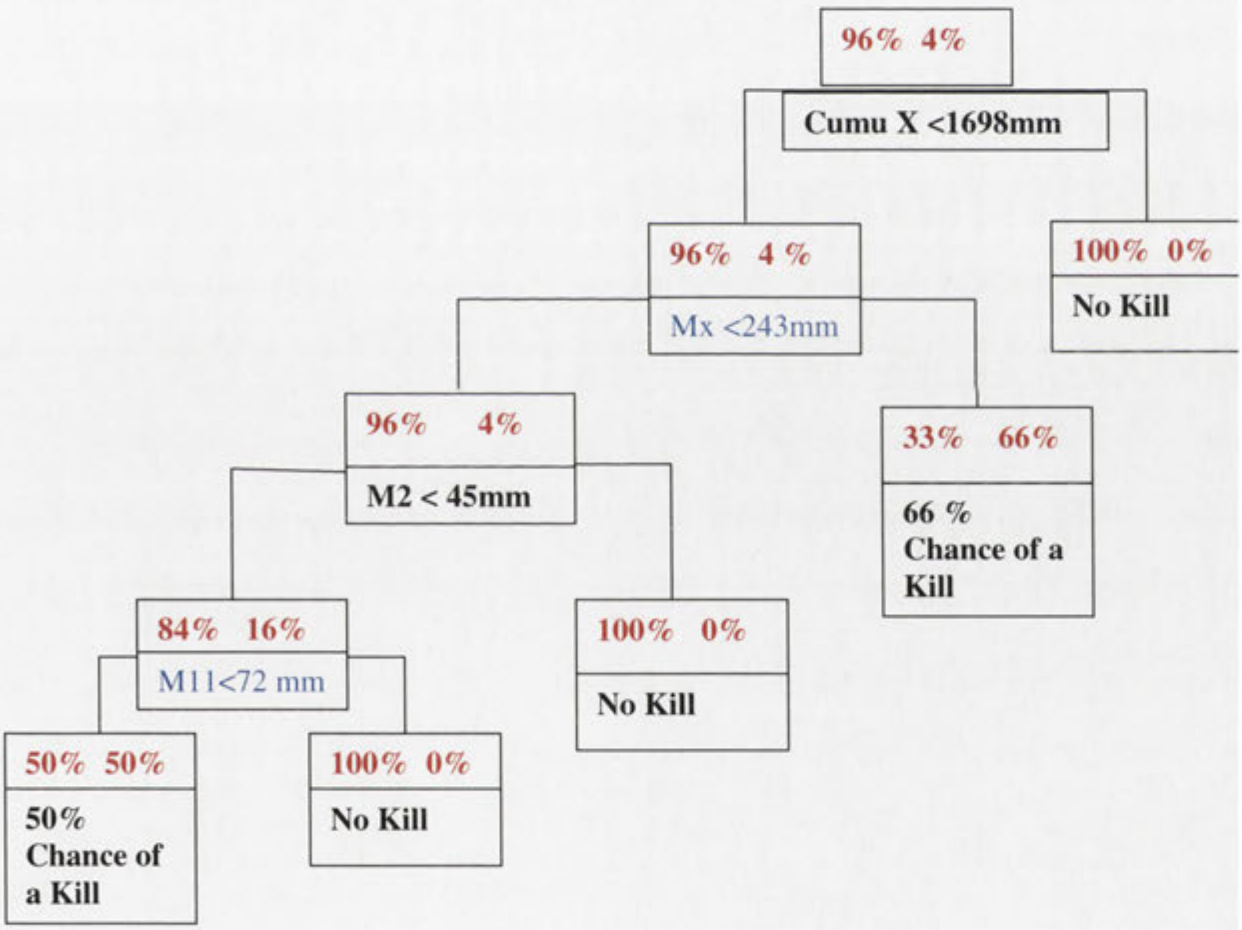


Figure 7.18 Probability tree for predicting fish kills using 12 monthly cumulative rainfall data (Cumulative rainfall values less than X mm follow the left hand side of the tree. Values greater than X mm follow the right hand side of the tree). CumuX is the 12 monthly cumulative rainfall, Mx is the month of the fish kill event, M2 and M11 are the 2[nd] ***and 11th month before the event, respectively.***

The sensitivity of the model could be improved by using monthly rather than cumulative data. It is apparent that the method of cumulating the rainfall data causes any variation in data to be smoothed. The coefficient of variation decreases with increased smoothing. Although the 12 monthly cumulative data may be useful for drought analysis studies (Smith *et al.*,1992) its use may not always be warranted, especially if the month by month variability in rainfall during these extreme dry periods is a causative factor for any given phenomenon.

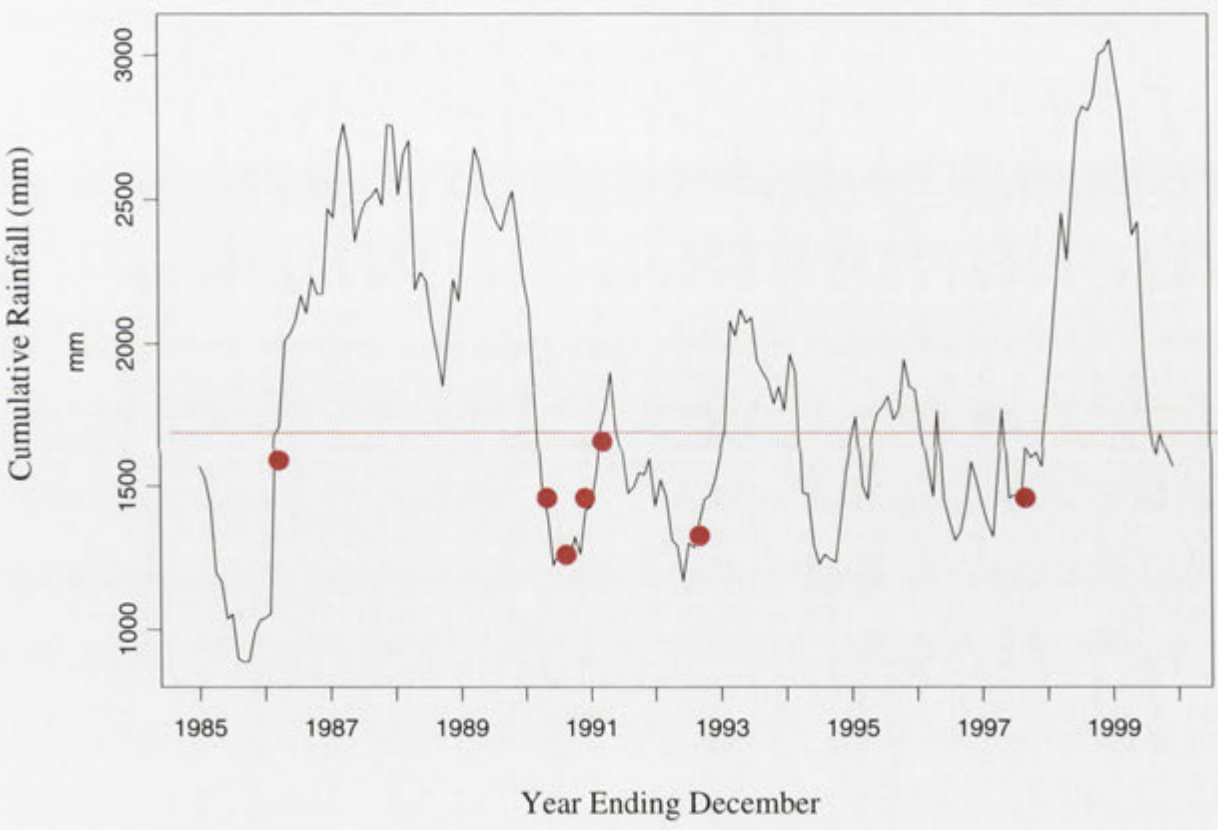


Figure 7.19 Cumulative 12 month rainfall from December 1985 to December 2000. There is a 50-66% probability of a fish kill event taking place if the cumulative 12 month rainfall is below 1698mm (Red line) depending on the actual monthly rainfall being more or less than 243 mm. There is no probability of an event taking place above this amount. (Red dots indicate fish kills).

7.7.2 Probability Tree Using Monthly Rainfall Data

A second probability tree was developed using monthly rainfall data in an attempt to improve the sensitivity of the model by taking into account the month by month variability in rainfall. Figure 7.20 shows the second probability tree for predicting the timing of a fish kill event. This probability tree is an improvement on the previous tree in that it is a stronger model in that the ability to predict a kill has jumped from 66% to 80%. For this tree model there is a mis-classification error rate of 4 in 180 and a residual mean deviance of 0.06756 or 13 out of 174.

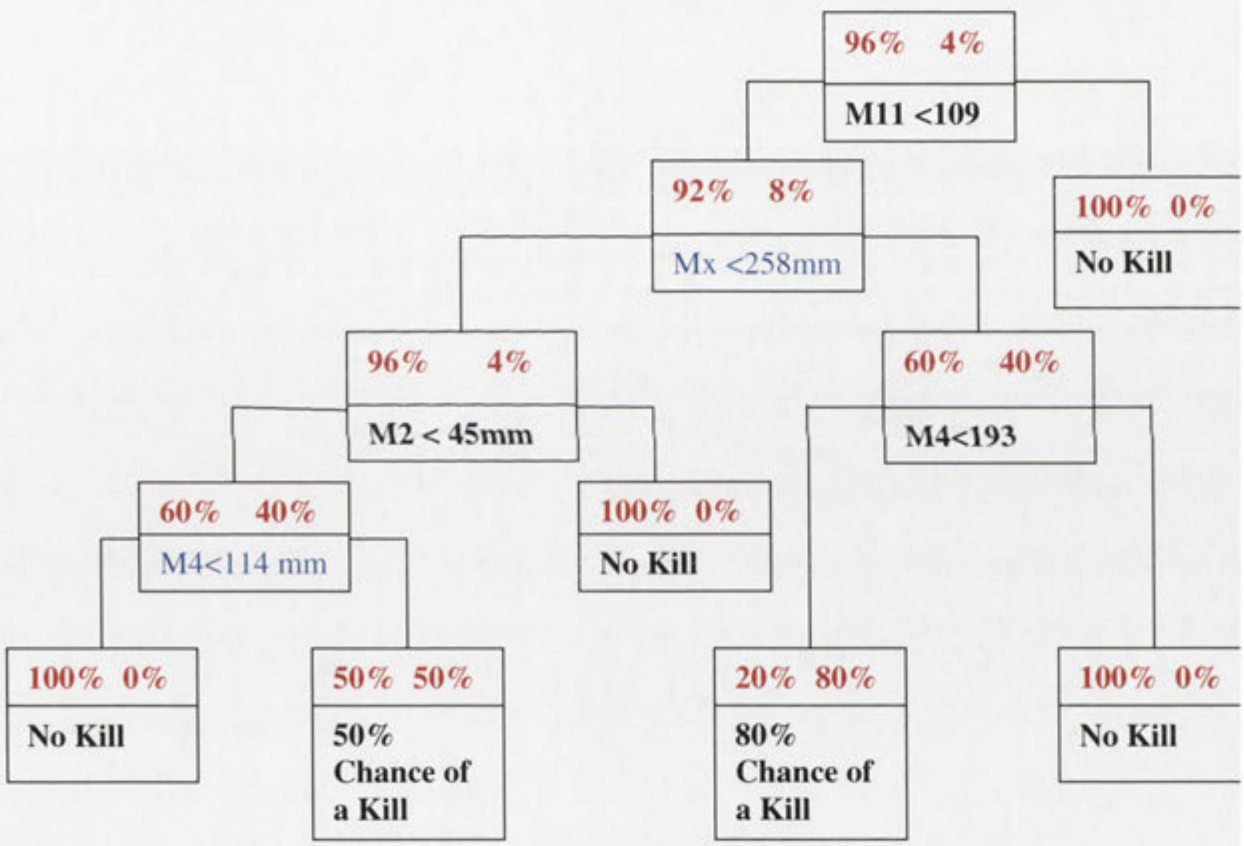


Figure 7.20 Probability tree for predicting fish kills from monthly rainfall events (Rainfall values less than X mm follow the left hand side of the tree. Values greater than X mm follow the right hand side of the tree). Mx is the month of the fish kill event, M2, M4 and M11 is 2, 4 and 11th month before the event, respectively.

The results of this probability analysis and the months which the model identified as the most critical in terms of fish kills, are summarised in Table 7.4. Predictions can be determined quite simply from the amount of rainfall which takes places during the critical months identified by the model. It is interesting to note that the model identified certain months of the year that are critical in determining the probability of a fish kill event.

The model identified four conditions for predicting an event and these are also summarised in Table 7.4. Fish kills were recorded during March, May, June, August and December (condition 1). The model indicates that if the average monthly rainfall is less than 109 mm during any of the months of April, June, July, September and January (condition 2), then there is only a 4 % probability of a fish kill event occurring in eleven months time. If, on the other hand, the rainfall is less than 193 mm during November or January or February or April or August (condition 3) and the amount of rainfall that falls during the month of the fish kill event (Mx)(condition 1) is greater than 258mm, then there is an 80% probability of a fish kill. This is, of course, assuming that condition 2 is also satisfied.

Table 7.4 Fish kill probability showing probabilities and the critical months.

Conditions Prior to the Event	**Probability**	**Rainfall Require-ment (mm)**	**Critical Months of the Calender Year**				
1)Actual Event (Mx)		< 258 or >258	March	May	June	August	December
2) The Eleventh Month before Mx	4%	<109	Apr	Jun	Jul	Sept	Jan
3) The Fourth Month Before Mx	80%	<193	Nov	Jan	Feb	Apr	Aug
4) The Second Month before Mx	50%	< 45 if >114 during M4	Jan	Mar	Apr	Jun	Oct

There is only a 50% probability of a fish kill event occurring if it is dry and rainfall is less than 45 mm, two months prior to the event. However, according to the model this condition only applies if the amount of rainfall during the fourth month before the event (Mx) exceeds 114 mm and that conditions 1 (Mx< 258) and 2 (M11 < 109) are satisfied. This situation applied to the 1998 fish kill event when a check was made of the historical records for this period. In summary, there are two conditions most likely to result in a fish kill event:

(1) When rainfall is low (<109mm) on the 11th month and (<193mm) 4th month before the month of the event with heavy rainfall (> 258mm) during the event month – there is an 80% probability.
(2) When rainfall is low (<109) on the 11th month and (<45mm) 2nd month before the month of the event with heavy rainfall (>114mm) on the 4th month before the event- there is a 50% probability. In this case the rainfall of the month Mx must be less than 258mm.

Clearly, this second probability tree improves the ability to predict the timing of a fish kill event. The model establishes the general rule that conditions must be dry on the eleventh month prior to the event and that according to the first model, the cumulative rainfall must be less than 1698 mm over the 11 months before the event. Unlike the first model, the second model has much greater sensitivity in identifying those months of the year that are seen as being the most critical in terms of a fish kill event taking place. Clearly, both probability trees are strong models for predicting fish kills, given the short length of the fish kill record.

In the case of the 80% rule (M11< 109mm, M4<193mm and Mx > 258mm)-(tree model 2) the probability tree does not reflect or identify the characteristic 'lag phase' discussed in section 7.4. It is interesting to note that the tree model has only identified the eleventh, fourth and second month before the event, as well as the month of the event, as the most critical months for a fish kill to take place. According to the model, except for the month of the event (Mx), these months must be fairly dry to trigger an event. What the probability tree fails to inform us is that the other nine months (not identified by the model) are not usually dry, but can in fact be quite wet, so long as the cumulative rainfall for the 11 months before the event does not exceed 1698 mm. The 50% rule (M11 <109, M2 <45mm, M4 >114mm and Mx < 258mm) on the other hand, reflects the characteristic 'lag phase' phenomenon discussed earlier in which the fourth month before the event needed to be wet with a dry month (<45mm)(ie M2) between M4 and Mx. In all cases the month of the event Mx was below 258mm, but was still generally wet with rainfall greater than 64 mm. This amount of rainfall was greater than the average lowest rainfall month during the year (ie September 60mm).

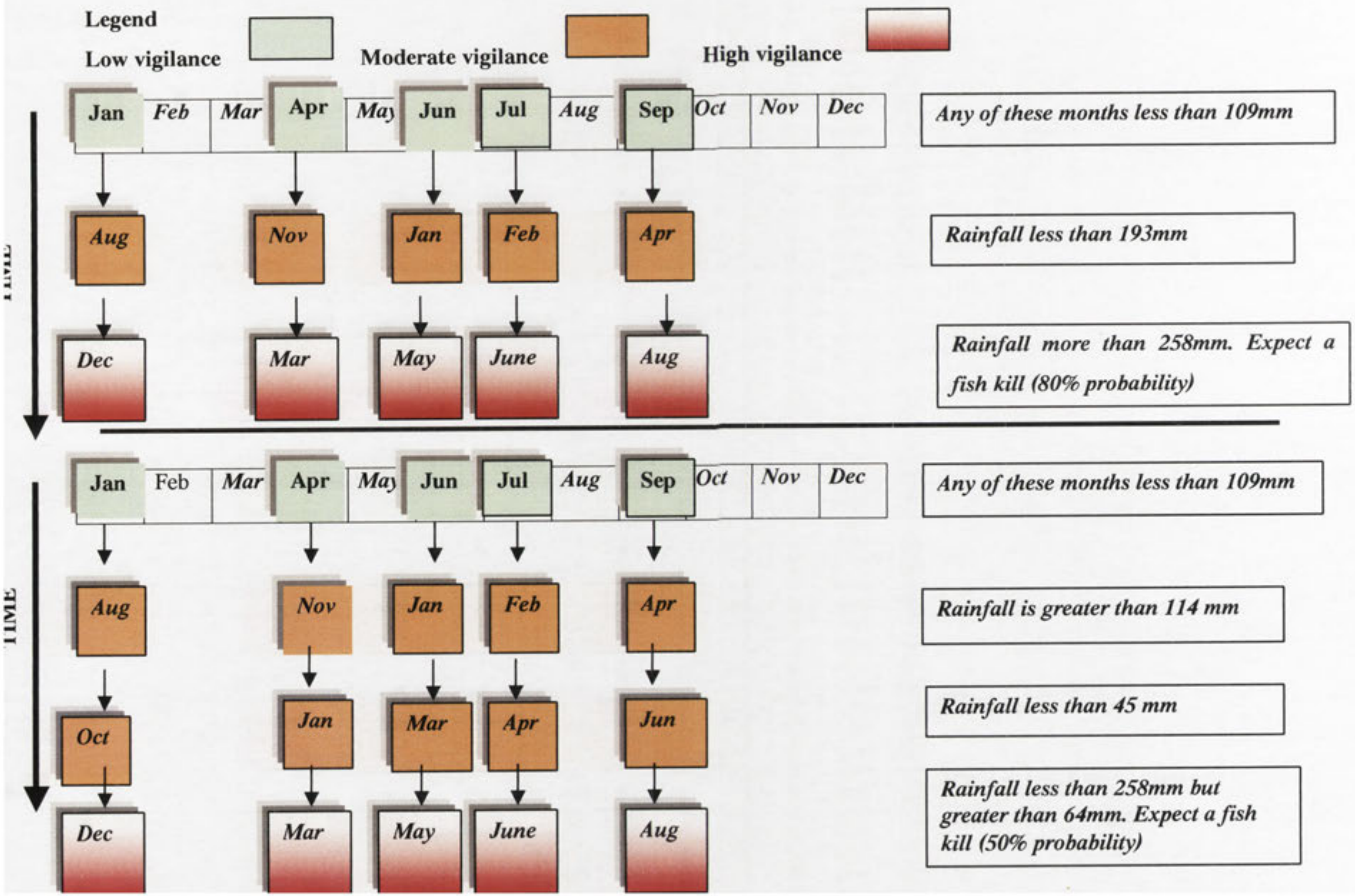
We should not rely on the probability tree as representing an alternative to a water balance model for predicting fish kills. The probability tree provides a different perspective on how climate can influence these events and could therefore be used in conjunction with stochastic weather models. It is important to remember, that geography and more specifically terrain, plays an important part in modulating localised weather patterns (Hutchinson, 1989). Thus, probability models almost certainly differ from one catchment to the next, so there is a need therefore, to develop a probability model that is specifically tailored for a particular catchment.

The model was developed using mean point rainfall data as opposed to spatial data. It is likely that these two data types could differ somewhat in monthly mean value. This should be taken into consideration when assessing the probability of an event taking place using spatial rainfall data alone. Most local governments would normally rely on point data for assessing the probability of an event taking place. For this reason, it is appropriate to develop the model using point data rather than spatially derived rainfall data, even though it may prove to be less reliable.

The fish kill probability model developed here is a useful tool for predicting fish kills up to 11 months in advance. Clearly, decision-makers can ensure that emergency management procedures can be adopted well in advanced when using this type of predictive model. This might include changes to floodgate control or diversion of up land flows around regions seriously affected by ASS, as well as increased preparatory measures for dealing with higher acid surface water loads. These measures and strategies are discussed in more detail in chapter 8.

From a catchment manager's perspective, it is far more practical to present the model as a probability chart as shown in Figure 7.21. This probability chart or management forecast planner for fish kills, provides a display of the months and their respective rainfall requirements that are most critical in terms of fish kills. The model could also be developed for other regions assuming that there are accurate rainfall and fish kill records available.

Figure 7.21 Fish Kill Emergency Management Forecast Planner (The first step in a predictive approach is that the cumulative rainfall for the preceding 11 months is less than 1698mm).



7.8 Discussion and Summary

The evidence presented here suggests that fish kills in the Tweed and Cudgen are closely linked to El Niño events. In eastern Australia, an El Niño event indicates that there is a high probability that conditions will be much drier than normal (Nicholls, 1988). However, as the rainfall records clearly demonstrate, periods of intense rainfall activity can occur during and after these events. It is the combination of extremely dry periods associated with periods of intense rainfall activity that led to fish mortalities. For all years in which a fish kill event was recorded, there was a distinct dry period in which rainfall percentiles were equal to, or below the 30 percent level. The ability to predict both the timing and frequency of these events depends on the availability of good rainfall and fish kill data. The lack of understanding between the interaction of large scale weather patterns and their impact on local climate variability, make it difficult to predict with any degree of accuracy the timing and frequency of future fish kill events. However, the results presented in this chapter point to an increased probability of an event taking place if conditions are dry 11 months before the event; that is, if the cumulative rainfall for the 11 months preceding the event is less than 1698mm. The model identified certain months of the year that are critical in determining the probability of a fish kill event. There is an 80% probability of a fish kill when the monthly rainfall is less than 109mm on the 11th month and less than 193mm on the 4th month before the month of the event and heavy rainfall (> 258mm) in the month of the event. The water balance determination study revealed striking similarities between fish kill events, showing that the height of the watertable and seasonal factors also contribute to fish kill events.

Climate variability associated with global weather systems is not the only contributing factor responsible for causing fish kills. The relationship between climate variability and the land must also be taken into consideration. It would appear that changes in localised weather patterns, the geography of the catchment and land management decisions also influence the timing and location of a fish kill. The rainfall surface maps provide a clear visualisation of the complex spatial patterns that occur on a month by month basis. These surface maps illustrate how changes in the local rainfall pattern in response to prevailing weather conditions, as well as topography, are important factors in predicting the location and magnitude of an acid discharge event.

The prevailing weather conditions, catchment size and its location relative to the sea, are key parameters in predicting the broader impacts of acidification on the aquatic ecosystem. The rainfall surface maps have shown that the Cudgen Catchment is particularly vulnerable to acidification events due to its small size and large floodplain to catchment area ratio and its close proximity to the sea.

Finally and most importantly, fish kills are, of course, not an indicator for measuring the magnitude, severity or extent of acid discharge on aquatic systems, as such events are unreliable in determining the duration, severity or extent of acidification. Fish kills are often reported long after the discharge event has taken place. Other factors associated with acidification, such as de-oxygenation and dissolved aluminium, may also be responsible (Sammut *et al.*, 1993; Driscoll *et al.,* 1980; Wendelaar Bonga and Dederen, 1986). In addition, fish generally avoid acidic water where possible, particularly in tidal reaches. Although macroinvertebrates and fish are often used as biotic indicators for assessing the health of aquatic ecosystems and for determining the capacity to support other life forms, they should not replace regular water quality monitoring using more conventional techniques.

The results presented in the last two chapters suggest, there are two important factors for the Cudgen Catchment that need to be addressed with respect to management at the catchment scale. The first involves the control of excessive volumes of water from heavy rainfall, following a dry spell. The second factor involves the re-design or re-engineering of drainage systems. These factors are examined in further detail in the next chapter.

CHAPTER 8
Remediation and Management Strategies

(Photo by Phil Johnston)

Chapter 8. Remediation and Management Strategies

8.1 Introduction

The implementation of effective and sustainable management strategies for regions affected by acid sulfate soils is largely dependent on finding a balance between environmental protection and acceptable land use by land owners. A primary impediment to the implementation of remediation and management strategies was the lack of recognition of problems relating to the use of acid sulfate soils. Continuing conflict between aquaculture and farming groups led to the establishment of the Acid Sulfate Soils Advisory Committee (ASSMAC) by the NSW State Government in 1994 (White, 2001a). ASSMAC was established to provide advice to government and to develop uniform guidelines for identifying acid sulfate soils (Ahern *et al.*, 1998). The Committee also provides direction on the management of acid sulfate soil landscapes with an emphasis placed on awareness, education and research. A national working party on acid sulfate soils was also established to provide a national approach to the management of these soils in consultation with industry and community groups. This working party developed the "National Strategy for the Management of Coastal Acid Sulfate Soils" (NWPASS, 1999). The national strategy acknowledges the need for an effective environmental hazard assessment process at the catchment scale.

The primary objective of these committees was to examine the options, techniques, timeframes and costs associated with the management and neutralisation of acid sulfate soils. In NSW, a Hot Spot Remediation program has been developed that prioritised those regions in NSW that require immediate remediation attention. The priority sites identified by the NSW Department of Land and Water Conservation cover an area of 55,000 hectares (ASSMAC, 1999b). The Cudgen Catchment heads the list of sites identified as having high priority for remediation works. The ASS Remediation Hot Spots program focuses on the use of effective site specific solutions and the need for increased community awareness relating to the use of appropriate remediation strategies and techniques for the identification of acid sulfate soils.

This chapter examines some of the land management options available and their effectiveness at reducing acid production and transport. These options relate to some of the issues raised in the previous chapter and they include the management of upland flows and the re-design of drainage systems.

8.2 Current Management and Remediation Options

There are several preferred options for the management of coastal acid sulfate soils; however, these can be broken down into three main categories. They include:

- Containment and prevention
- Dilution
- Neutralisation

8.2.1 Containment and Prevention of Oxidation

For acid sulfate soils that have not been disturbed through farming and drainage activities, the need to maintain anoxic conditions within the sulfidic zone in the soil profile is essential. This can be achieved by ensuring that the watertable level is maintained above the sulfidic layers, thereby providing an oxygen-free environment. A high watertable strategy has proven to be effective in preventing the oxidation of potential acid sulfate soils in some south-east Asian countries (Yin and Chin, 1982). The practice of maintaining a high watertable to reverse the acidification process has been successfully used for grasslands (Dent, 1986) where there is a reduction in iron III oxides by microbes that use high organic matter in the soil. This reaction reduces sulfate to monosulfides and precipitated iron III is reduced to iron II. The reaction is catalysed by microbes in the soil that use organic matter in the process. Without sufficient organic matter present in the soil, the reduction of iron III to iron II in the sediments cannot occur at a fast enough rate to prevent iron III from oxidising pyrite. Iron III can continue to oxidise pyrite and liberate more acid in the absence of oxygen.

Where there is little available organic matter, soil acidity cannot be reversed through maintaining high watertables or through the re-flooding of sulfidic low lands. In addition, there are difficulties in maintaining watertables at the desired depth in soils where the hydraulic conductivities are low and on such a large scale (Tuong, 1993). In regions where rainfall is highly variable it may also be very difficult to maintain water levels above the sulfidic layer (White *et al.*, 1997). In places where drainage has resulted in the oxidation of sulfides, there exists a vast store of acidity in the soil profile which can leach out resulting in acid discharge. This process can continue for a 100 years or more (White *et al.*, 1997). Under these circumstances, the containment of acid within the soil profile is a reliable strategy in preventing or reducing acid discharge.

The containment of acid within the soil profile can be achieved through the implementation of suitable watertable management practices. In the McLeods Creek region of the Tweed Catchment where deep rooted crops such as sugar cane is grown, land holders have used laser levelling and the reduction of drainage density to contain acid (White *et al.*, 1999a). Laser levelling of fields involves using a laser beam mounted on a plough which constantly adjusts the height of the plough according to the required slope of the land. Laser levelled paddocks usually have a design gradient of 1/1000 (R Quirk, personal communication, 2001). Non-laser levelled fields often contain depressions that trap surface water and cause water logging. The infiltration of rainwater on non-laser levelled fields results in a rise in the watertable and the subsequent movement of acidic groundwater to the soil surface. Laser levelling allows for the quick removal of non-acidified surface water from the field to the drainage system with a marked improvement in water quality (White *et al.*, 1997). The practice has also enabled a reduction in the drain density (White *et al.*, 1997).

Another form of containment is the capping of acid sulfate soils with a relatively impermeable material such as compact clay. Capping has been used in the mining industry to control the release of leachate from overburden heaps and acid rock drainage from mining sites (White and Melville, 1996). Capping slows down the rate of oxygen diffusion and surface water infiltration into the acid sulfate soil layer and controls the rate at which acid water moves to the soil surface. Furthermore, capping also pushes oxidisable sulfide material further down into the soil profile and into regions where temperatures are lower in unconsolidated soils (White and Melville, 1996).

8.2.2 Dilution

Dilution involves the mixing of non-acidic water with acidic water to increase pH. The strategy involves the release of acid into the stream or river system at a particular discharge point under controlled conditions. Seawater has been used to dilute acid waters in some coastal floodplains where there is sufficient tidal exchange between the receiving waters and the acid drainage water. Floodgates provide the mechanism for controlling the extent of tidal exchange and acid release but have also been blamed for interfering with environmental flows and fish mortalities (Sammut *et al.*, 1996). Due to the presence of bicarbonate in the seawater the dilution of acid water with seawater is also a form of acid neutralisation. During dry periods small amounts of acid are released from floodgates into estuarine waters and are quickly neutralised by saline water (Sammut *et al.*, 1996). However, the use of floodgates to control acidic discharges should not be considered as the sole solution to the problem of acidification.

8.2.3 Neutralisation

Neutralisation involves the chemical reaction between a neutralising agent such as lime, to increase pH. The use of lime to neutralise acid has been used for a variety of applications. In Norway, Traaen e*t al.*(1997) applied lime to streams to neutralise the effects of acid runoff from acid rain. Lime has also been used in the mining industry to treat acid mine drainage (Helms and Heinrich, 1997). Lime can be applied either directly to the land or to surface waters. Direct application of lime to the land can be expensive due to the large quantities required to neutralise the acid already in the soil. White and Melville (1996) have determined that ASS which contain up to 5% (wt/wt) of pyrite is equivalent to around 80kg of pyrite per cubic metre. Taking into account a safety factor of 50%, this equates to 120 kg of sulfuric acid per cubic metre. Approximately 100 kg of calcium carbonate or 55 kg of magnesium oxide per cubic metre is required to effectively neutralise this amount of stored acidity. As an alternative, lime can also be added directly to the surface waters.

Saline water is far more effective in neutralising acid water than fresh water alone. Seawater has a neutralising capacity equivalent of 0.1 to 0.125 kilograms of sulfuric acid per cubic metre (White and Melville, 1996) compared with fresh stream water which has a neutralising capacity of around 0.05 kilograms per cubic metre (Dent and Bowman, 1993).

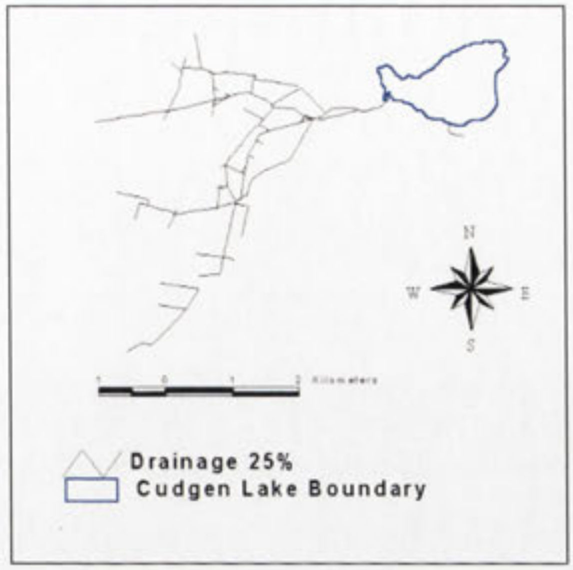
8.3 Drainage Management and Reduction Strategies

There is some anecdotal evidence which suggests that drain reduction strategies in combination with laser levelling of the floodplain can reduced acid discharge by up to 80% (ASSMAC, 1999b). To date, there is no hydrological modelling to show the real impact of drain reduction strategies on acid discharge. Chapter 5 of this work revealed the significance of the drainage network on the relocation of the acid within the floodplain and the changes in the floodplain hydrology. It is not feasible to remove all the drains within the Cudgen floodplain and return these sulfidic low lands back to their natural state as rehabilitated wetlands. However, a reasonable reduction in the number of drains within the current drainage network or the re-engineering of existing drains may provide an effective remediation strategy.

8.3.1 Drainage Reduction Strategies for Reducing Acid Outflows

The impact of drainage on acid outflows was examined using the methodology discussed in section 4.2.18, Chapter 4, p108-109. The model was used to assess the impact of different drainage densities on the export of sulfuric acid. Density is normally the length of drain per hectare. This research examines the percentage reduction of the current drainage. Four different drainage scenarios (minimum drainage, 25% drainage, 50% drainage and current drainage) were used to compare the impacts of acid transport and loads across the floodplain and into Cudgen Lake. Figure 8.1 shows the range of drainage scenarios modelled. The minimum drainage density is approximately equivalent to the pre-existing natural drainage in the catchment.

Minimum Drainage Capacity



25 % Drainage Capacity

50 % Drainage Capacity

Current Drainage Capacity

Figure 8.1 Drainage Scenarios modelled for the Cudgen Catchment.

8.3.1.1 Surface Water Concentrations

The calculation of acid surface water concentrations was determined from the annual sulfuric acid land loads and runoff for the catchment, using the model methodology discussed in Chapter 4. Figures 8.2–8.6 show the modelled acid concentrations in surface waters under four drainage regimes in the Cudgen Catchment.

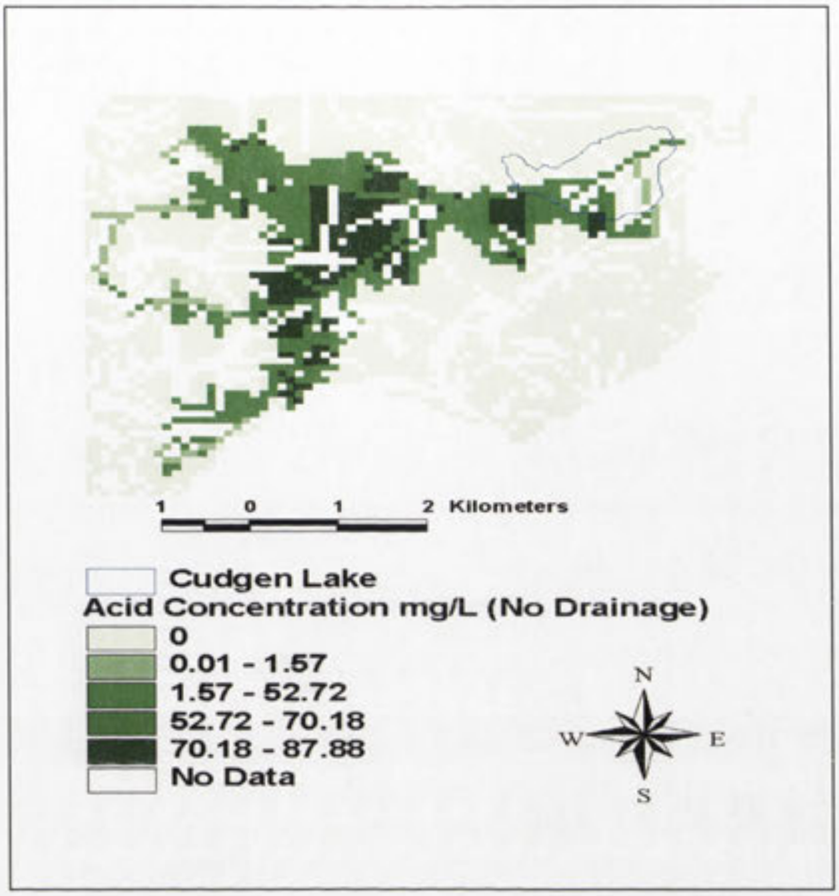


Figure 8.2 Sulfuric Acid Concentration in Surface Water (No Drainage).

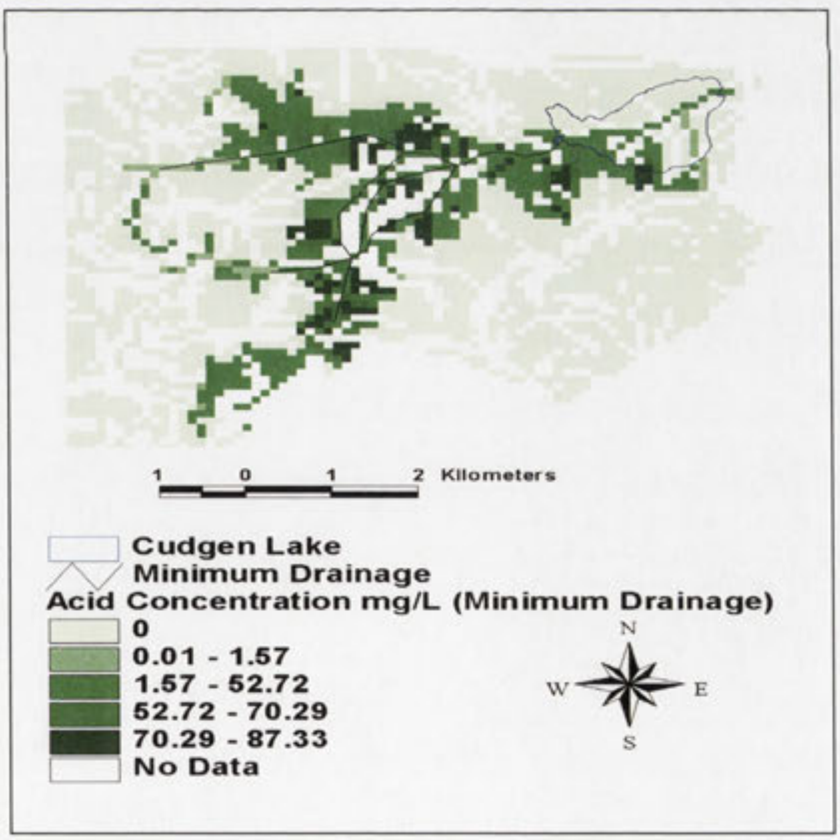


Figure 8.3 Sulfuric Acid Concentration in Surface Water (Minimum Drainage).

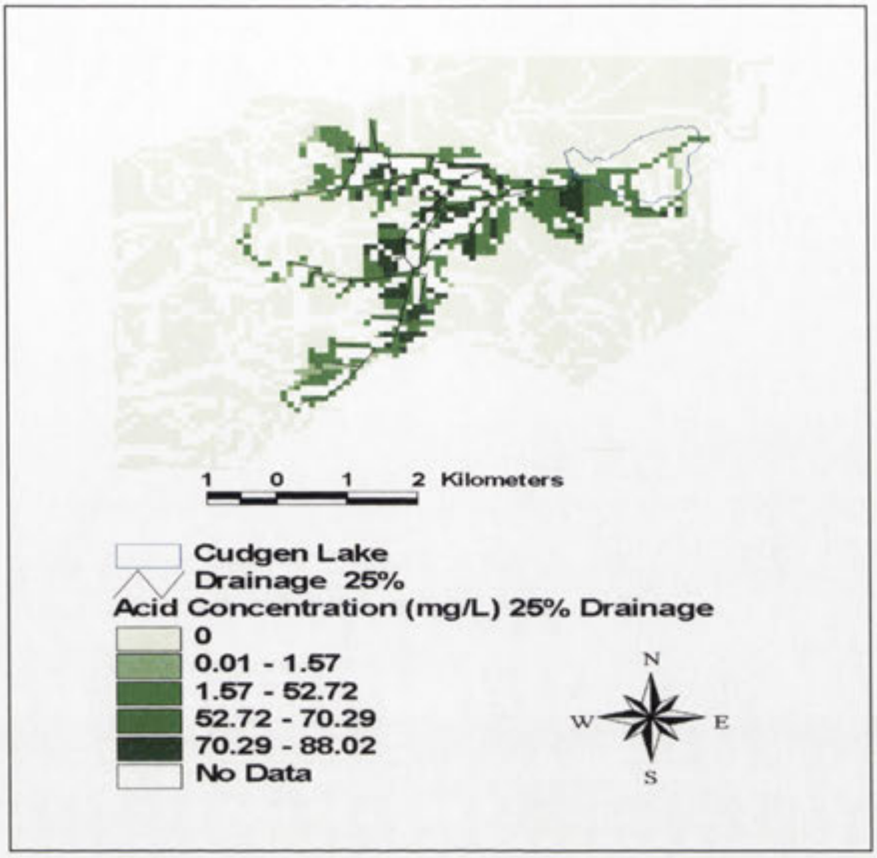


Figure 8.4 Sulfuric Acid Concentration in Surface Water (25% Drainage Capacity).

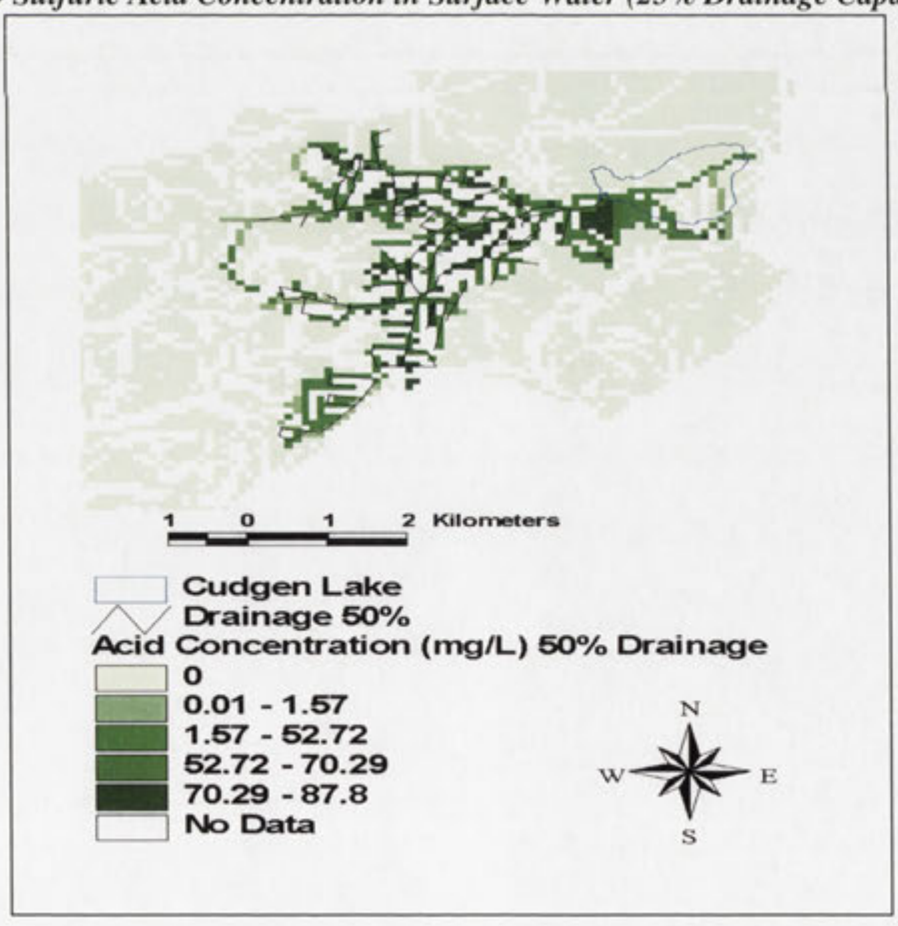


Figure 8.5 Sulfuric Acid Concentration in Surface Water (50% Drainage Capacity).

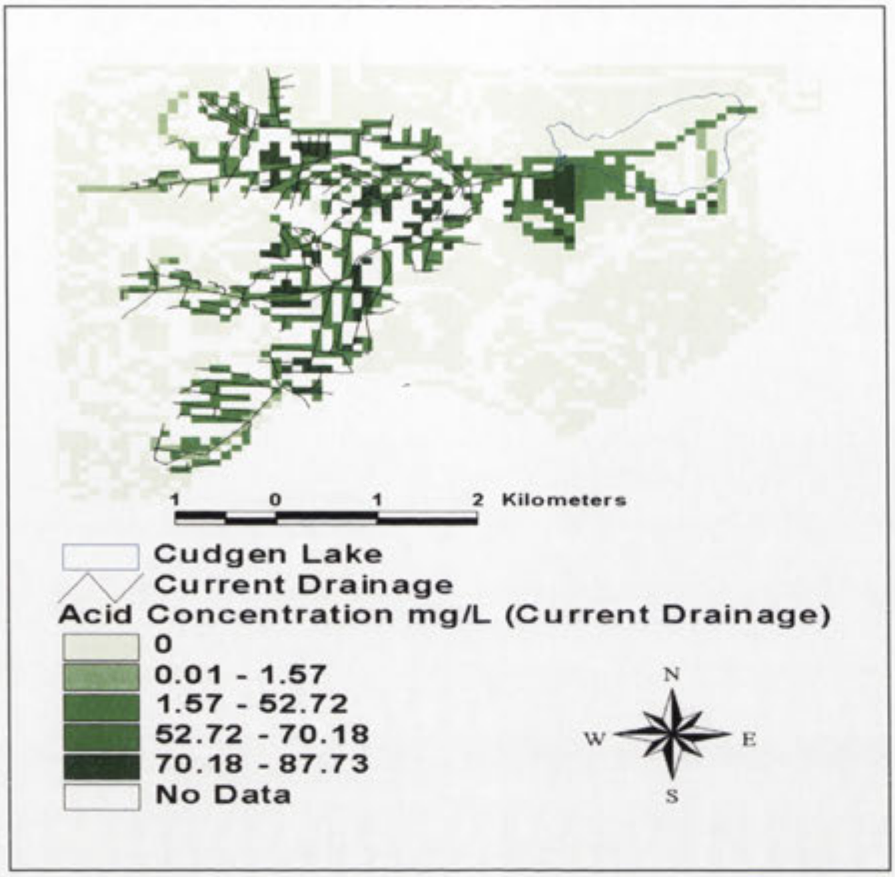


Figure 8.6 Sulfuric Acid Concentration in Surface Water (Current Drainage Capacity).

The constructed drainage systems in the Cudgen Catchment are designed to remove water from the floodplain as quickly as possible in order to prevent water logging (White *et al.*, 1999a). The results in Figures 8.2-8.6 show the efficiency of the drainage network in removing acid surface water from the floodplain to the drainage network under different drainage densities. An examination of these results suggest that the 50% and current drainage capacities are equally effective at transporting acid surface water from the floodplain to the drainage network. The model demonstrates that the translocation of acid surface water from the field to the drains is just as effective when using lower density drainage systems. If half the number of drains were to be filled in, the capacity of the reduced drainage system at removing surface water would probably be just as effective as the current drainage system.

However, there is a reduced capacity in drainage efficiency at 25% of the current drainage capacity (Figure 8.4). The efficiency of the drainage network at removing acid surface water from the floodplain is even more significant under minimum drainage where a much greater proportion of surface acidity remains confined to the floodplain. The average concentration of acid confined to the drains and the floodplain under the different drainage scenarios is listed in Table 8.1. The average concentration of acid confined to the floodplain and in the drains depends on the drainage density. The floodplain area had an annual mean acid concentration of 4.6 mg/L under minimum drainage conditions and 1.10 mg/L for the current drainage network. Thus, a decrease in drainage density corresponds to high acid concentrations remaining on the floodplain.

The large standard deviations shown for some scenarios indicate a high degree of variability of concentration, across the catchment. The variability in acid concentration within the drainage network is fairly consistent between drainage densities. However, acid concentrations are more variable at the floodplain level especially as drainage density decreases.

Table 8.1 Average annual concentration of acid in surface water for drains versus the floodplain (Maximum concentration shown in brackets).

	Average Annual Acid Concentration (mg/L) for Drains vs Floodplain			
Drainage Capacity	Drainage Network	SD	Floodplain	SD
Current	28.0 (87.7)	29.4	1.10 (87.7)	8.4
50 %	31.0 (87.8)	29.7	1.80 (87.7)	10.5
25 %	29.8 (87.6)	30.6	2.23 (88.0)	13.1
Minimum	26.4 (87.4)	24.6	4.65 (88.3)	14.9

Apart from an increase in the mean acid concentration across the floodplain, a dramatic reduction in drainage density could also result in some degree of water logging through increased surface water retention, unless the floodplain is laser levelled. Table 8.2 shows the percentage of surface water retained by the floodplain under different drainage regimes. Most of the surface water eventually ends up in the lake regardless of the drainage density. There was only a 17 % difference in surface water retention between the current drainage and the minimum drainage scenarios and a 7 % difference between the 25% and current drainage network. Although most of the surface water is removed under different drainage regimes, what is important to remember here is the surface water retention time. What the modelling does not tell us is the time it takes for the surface water to be removed from the floodplain under different drainage conditions. The residence time for surface water has been dramatically reduced from around 100 days under natural conditions to around 5 days for well-drained floodplains (White *et al.*, 1999a). A majority of crops grown on coastal lowlands cannot withstand extreme waterlogging for more than 5 days (Bouwer, 1974) especially sugar cane (which is still grown in only a small area of the Cudgen Catchment).

Table 8.2 Percentage of surface water retained by the floodplain under different drainage regimes.

Percentage of Surface Water Retained by the Drainage Network and the Floodplain		
Drainage Capacity	**Drainage Network**	**Floodplain**
Current	74	26
50%	72	28
25%	67	33
Minimum	57	43

Reverting the floodplain to a wetland through the elimination of the drainage system would increase the retention time of acidified water and may reduce the frequency of acid discharge events. Such an ambitious project would meet strenuous opposition from land owners. When conditions are extremely dry and hot there is an increased likelihood that most of the surface water would eventually evaporate in the undrained situation. This may result in significant concentrations of acid in the surface soil to be washed away in subsequent flood events.

There is the possibility that re-flooding may result in the production of iron monosulfides from the microbially catalyzed reaction, in which sulfate is reduced to sulfide and iron III is converted to dissolved iron II (Dent, 1986). Monosulfides are more unstable under oxic conditions than iron pyrite and can re-oxidise resulting in the further oxidation of iron pyrite (White *et al.*,1997). Another problem associated with the re-flooding of sulfidic lowlands is the continued release of stored acidity from the soil profile. Since there is no soil water storage capacity under flooded conditions, more stored acidity may be liberated. It is simply not practical or economical to neutralise this stored acidity because of the large volumes of lime required to neutralise it.

The application of re-flooding to control acidification appears feasible in some south-eastern countries such as Thailand (Yin and Chin, 1982), where rainfall is fairly consistent and where there is a considerable store of labile organic matter in the soil profile. In Australia, this type of rehabilitation is simply not practical due to the high degree of rainfall variability (White *at al.*, 1997), a deficiency in available organic matter in the oxidised subsoils of land used for cane farming (Wilson, 1995) and its compatibility with existing land uses. During extremely dry periods the surface water retained by the floodplain eventually dries out, exposing the top soil to large amounts of acid species and increasing the chances of severe acid scalding. The findings discussed in Chapter 6 indicate that climate change may result in even greater rainfall variability creating conditions that are more favourable to acid production and discharge.

It is unlikely that a majority of land holders would accept a policy of drain reduction without some form of flood mitigation or land-use changes to compensate for an increase in water retention especially over long time periods. It is also unlikely that farmers or land owners would be prepared to have their properties reverted to a natural wetland. A recent survey showed that a common concern amongst a majority of farmers and land holders is the conversion of productive agricultural land into protected wetlands (Woodhead, 1999). Many believe that they should be entitled to financial compensation incurred as a result of a loss in productivity or resale value (Woodhead, 1999). It is essential that drain reduction strategies are carried out in concert with laser levelling in order to prevent water logging and to minimise water infiltration.

8.3.1.2 Acid Surface Water Loads

The annual accumulated sulfuric acid surface water loads for the Cudgen Catchment were determined for all four drainage scenarios using the methodology discussed in chapter 4. Figures 8.7–8.10 show the accumulated sulfuric acid surface water loads under different drainage scenarios.

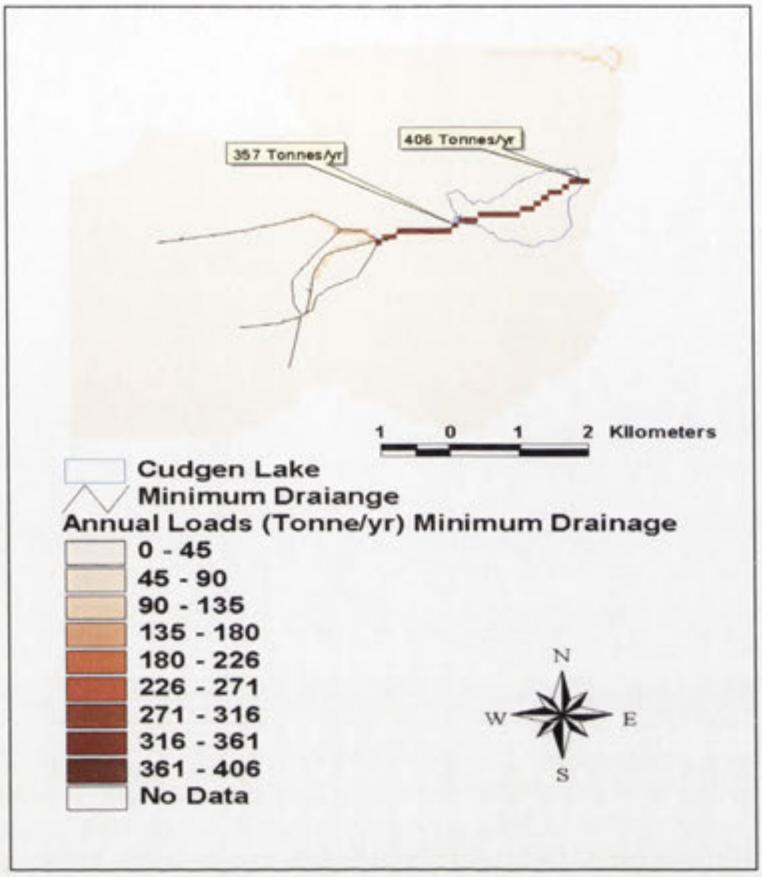


Figure 8.7 Sulfuric Acid Surface Water Loads (Minimum Drainage).

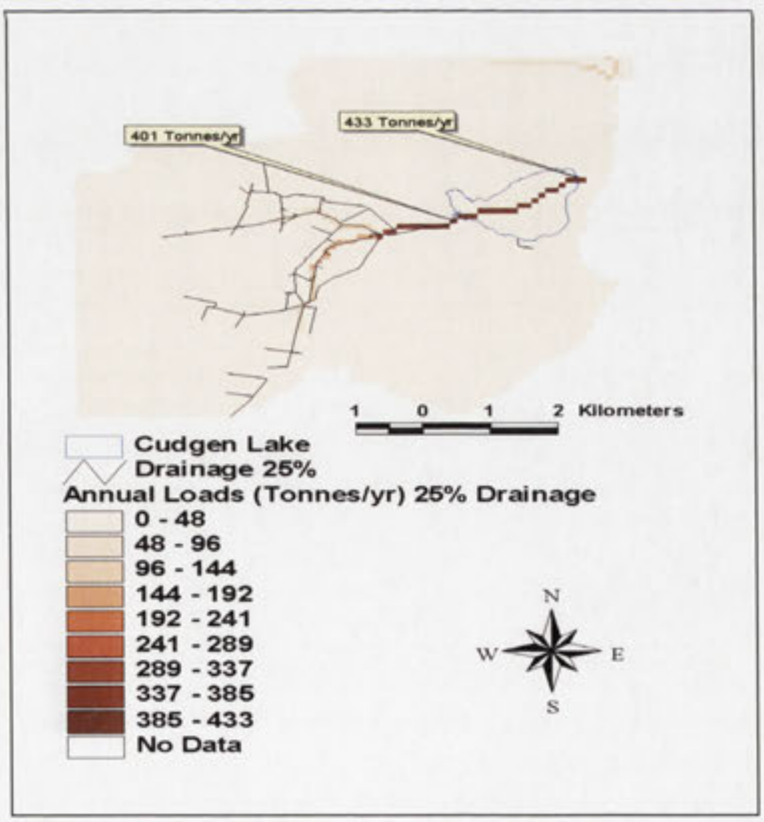


Figure 8.8 Sulfuric Acid Surface Water Loads (25% Drainage Capacity).

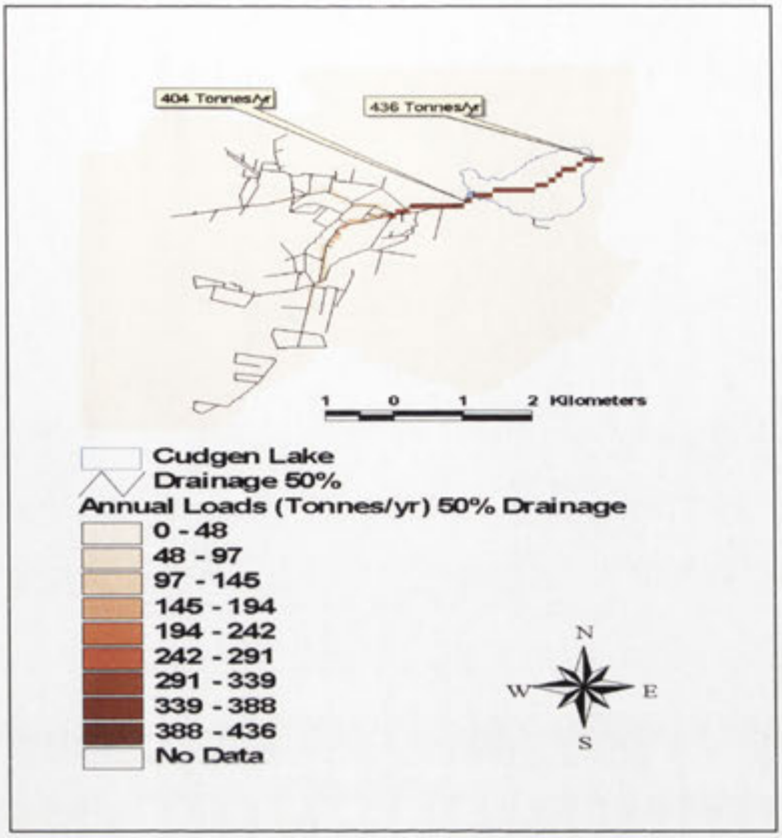


Figure 8.9 Sulfuric Acid Surface Water Loads (50% Drainage).

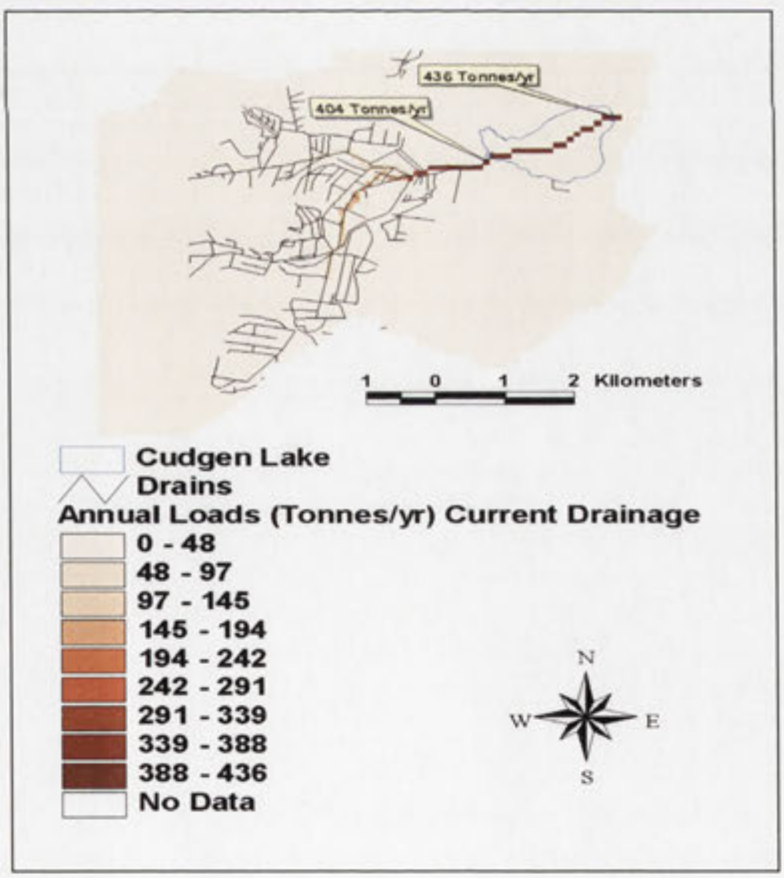


Figure 8.10 Sulfuric Acid Surface Water Loads (Current Drainage Capacity).

The determination of acid surface water loads indicate that no significant change was observed in the modelling results (Figures 8.7-8.10) between the sulfuric acid surface water loads entering and exiting Cudgen Lake for all drainage scenarios, except in the case where a minimum drainage enforcement was applied to the model. There was a two tonne reduction in sulfuric acid entering Cudgen Lake under 25% drainage density and no change under the 50% drainage density scenario. The results suggest that the drainage capacity for both the 25 and 50 % densities, was just as effective at accumulating acid surface water loads, as the current drainage density. However, under minimum drainage conditions there is around a one-tenth reduction in the surface water loads entering Cudgen Lake. This represents a 47 tonne reduction in sulfuric acid transported to the lake. Clearly, a substantial reduction in the number of drains is required before there is any impact at all on the transportation of acid surface water loads. Normally, we would expect lower production rates from lower drainage densities (White *et al.*, 1997). Therefore, the results obtained here could be a direct consequence of the model that assumes there is a fixed rate of acid production irrespective of the drainage density.

The real issue relating to the impact of the drainage system on the export of acid to aquatic ecosystems is one of time and location. Drainage and flood mitigation schemes have drastically reduced the residence time for the water in the floodplain, increasing the rate at which acid waters move from the floodplain to estuarine reaches, coastal river systems and embayments (White *et al.,*1999a). Once acid surface water is effectively translocated to the drainage network, the speed at which it is delivered from the floodplain to the ecosystem is greatly increased.

Although the modelling results suggest that there are no real significant changes in the accumulated surface water loads entering Cudgen Lake under a range of density regimes, the rate at which acid surface waters are delivered to the lake environment for the various drainage densities, should also be considered. A small and slow acid discharge event is quickly neutralised by sea water. However, a rapid discharge event with faster flows would have a much more immediate impact on the water quality of Cudgen Lake. In fact a small, simplified drainage network may prove to be more detrimental than the current system with its network of bends and drainage lines. A simple drainage system, with fewer drains and continuous drainage lines, would translate into increased flow rates and higher fluxes. This might explain why there is little change in the surface water loads entering Cudgen Lake even though the density has been reduced substantially (ie from current to 25% and 50% drainage densities).

These results clearly suggest that drainage minimisation per se does not appear to be an effective means of reducing acidification unless measures are also taken to reduce the amount of surface water flow. The main priority for land managers is to prevent or minimise the amount of acid surface water from being translocated to the drainage system in the first place without any additional retention in floodwater. It has been shown that good drainage design is an essential element in reducing acidic discharge while at the same time preventing water logging (Yang *et al.,* 1999; White e*t al.*, 1997). White *et al.*(1997) recommends the use of wide shallow drains to prevent waterlogging and reduce oxidation in undrained areas. Floodplains should be left undrained if the sulfidic layer is less than 0.5 metres from the soil surface. Otherwise, in regions where the sulfidic layer is 2.0 metres deep, care should be taken to avoid digging further than one metre from the sulfidic layer. The use of improved drainage design to reduce acid outflows in previously drained regions, will prove to be a challenge. An essential requirement in the design of drainage systems is an understanding of the hydraulic properties of the soil and the rainfall characteristics of the catchment. The effects of drain redesign and configuration on acid discharge and surface water transportation is an area that requires further research.

The diversion of upland flows around contaminated sites, in conjunction with levee banks to prevent the lateral movement of contaminated waters into major diversion drains, is another strategy which should also be considered as a way of reducing flows. However, the construction of levee banks should be carefully designed in order to prevent any detrimental change in the watertable height in periods of very heavy rainfall.

Alternatively, it is possible to ensure that the acid is contained within the soil profile by providing an adequate soil water storage capacity, by ensuring that the watertable remains low. These options can be achieved through the use of correct land management strategies.

8.4 Land Management Options

8.4.1 Groundwater Management

In chapter 5 it was shown that the amount of rainfall required to produce an acid discharge event depends on the current soil water storage capacity. The height of the watertable in this region is controlled by evapotranspiration from deep-rooted plants and crops such as sugar cane. The planting of trees and sugar cane in these floodplain regions increases the capacity of the soil to absorb more water through watertable lowering. A low watertable provides a greater soil water storage capacity and reduces acid outflow events (Wilson, 1995). Therefore, deciding on a suitable groundwater management strategy often depends on appropriate land use activities and management practices. Since the infiltration of surface water affects the watertable dynamics, these strategies might include the control of surface waters through the alteration of flow paths or through planting deep rooted crops or trees.

8.4.2 Changes to Upland Flows

Altering the flow characteristics of the catchment by diverting uncontaminated water around acid sulfate soil regions, contributes to an improvement in the water quality down stream. The diversion of unpolluted water around acid drainage is a technique commonly practised at mine sites in Australia (Murphy *et al.*, 1999). In this section, the diversion of upland flows from the Clothiers and Christies Creeks was modelled using current and minimum drainage density scenarios. In order to prevent any overspill of acid water into the diversion channel, it was necessary to create an additional drainage line between the diversion channel and the acid sulfate soil regions displayed on the ASS risk maps (Figure 8.11). This additional drainage line represents a containment channel or levee bank. The incorporation of these new drainage lines, involved the creation of two new flow direction paths within the 100 metre DEM. In some places it was necessary to transect the 5 metre and in some cases the 10 metre contour line to avoid regions containing ASS. Surface water loads and annual flow rates were determined for the levee and diversion channel for each scenario. The diversion of upland flows from Christies Creek involved diverting surface flows away from the Cudgen Catchment into the neighbouring low-lying catchment.

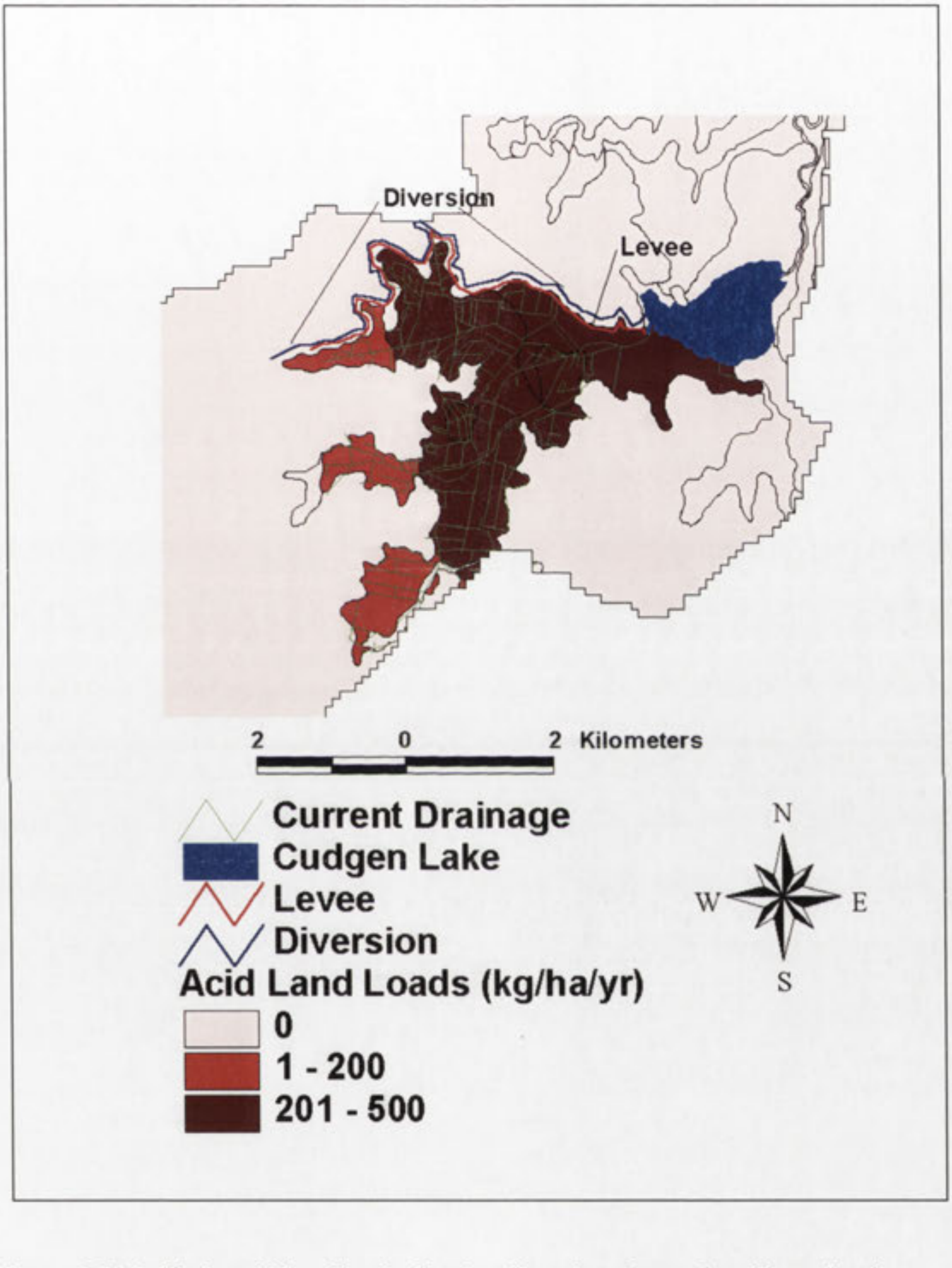


Figure 8.11 Sulfuric acid land loads showing diversion channel and levee bank.

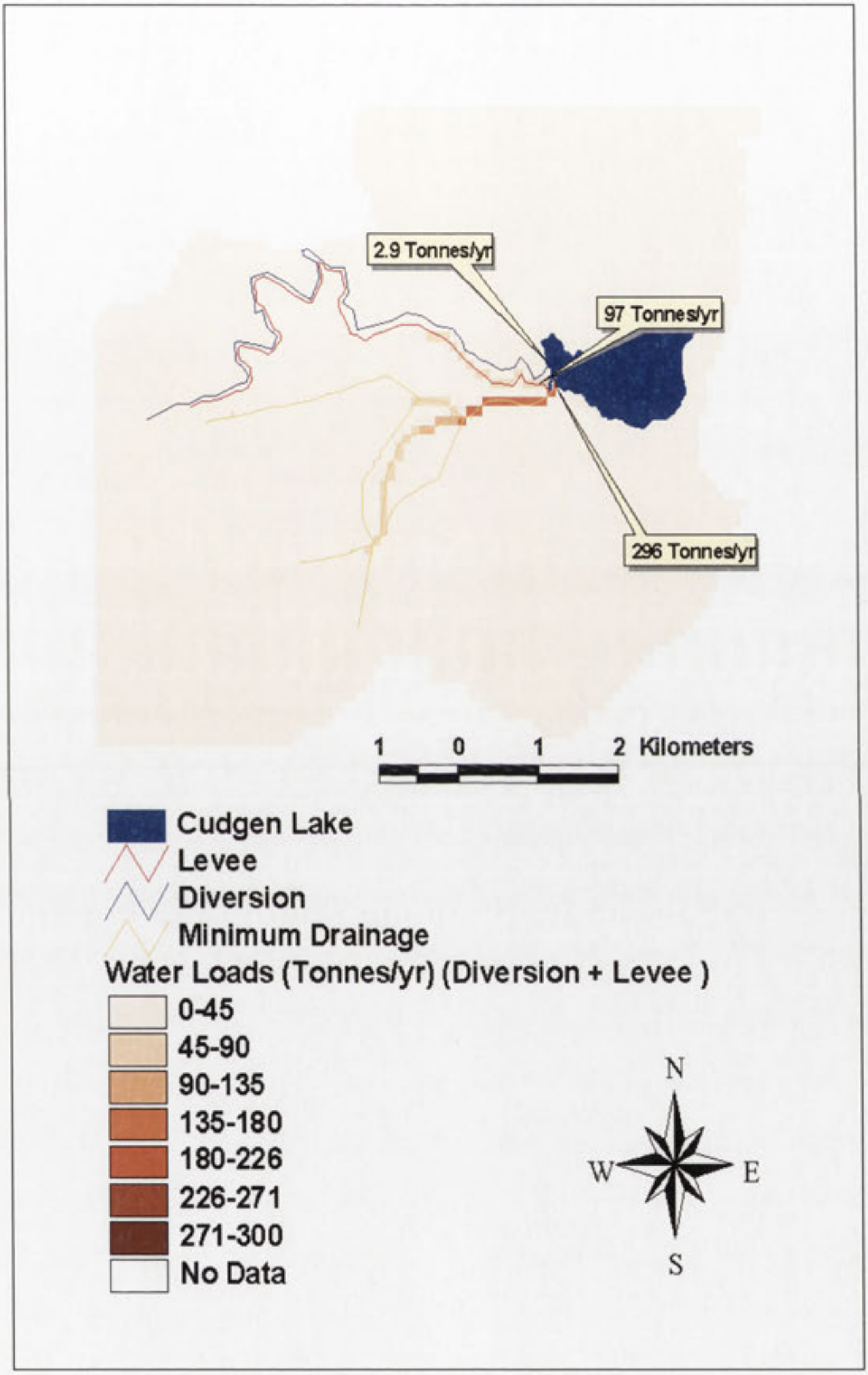


Figure 8.12 Surface water acid loads under minimum drainage showing diversion channel and levee.

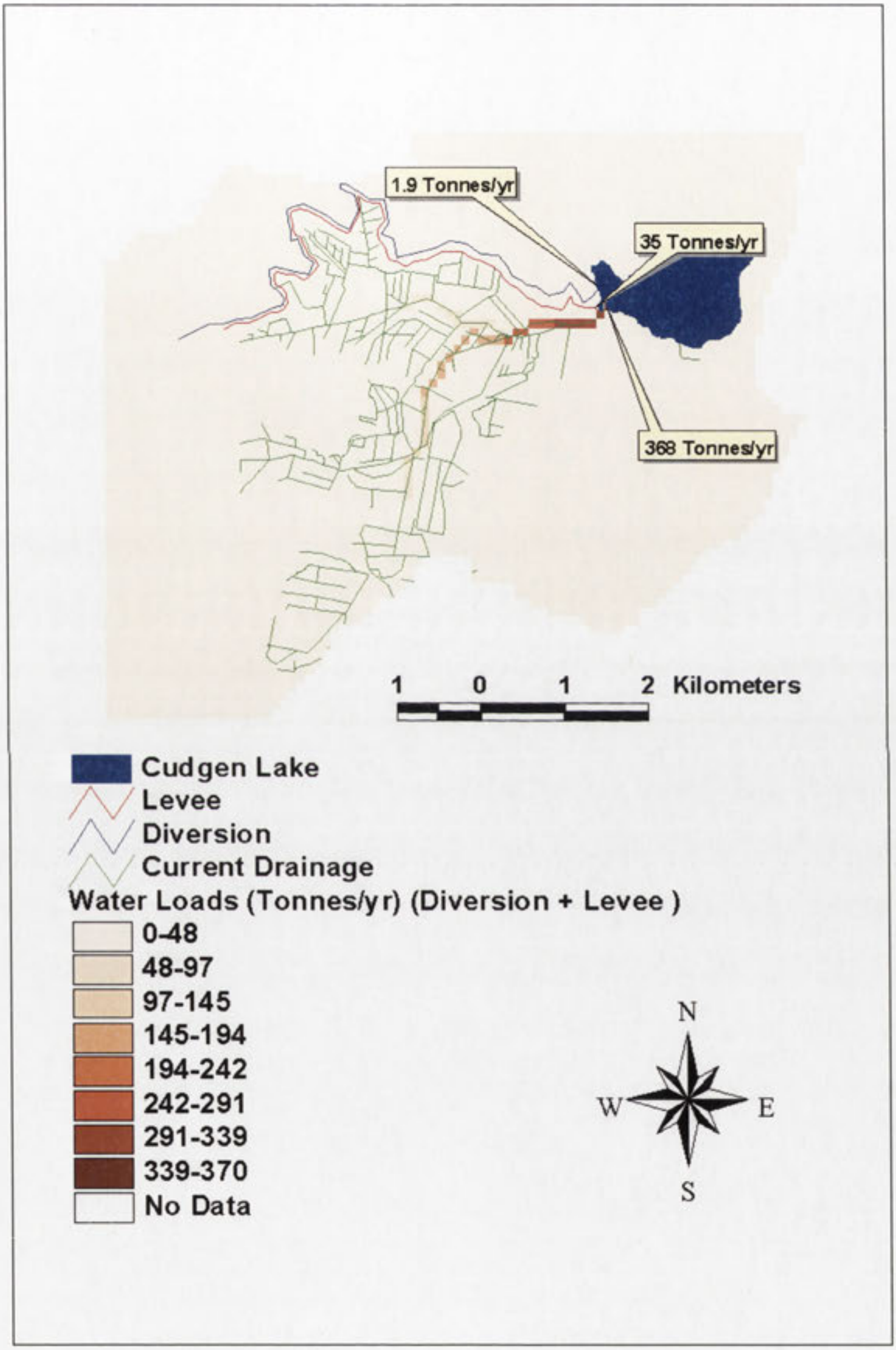


Figure 8.13 Surface water acid loads under current drainage showing diversion channel and levee.

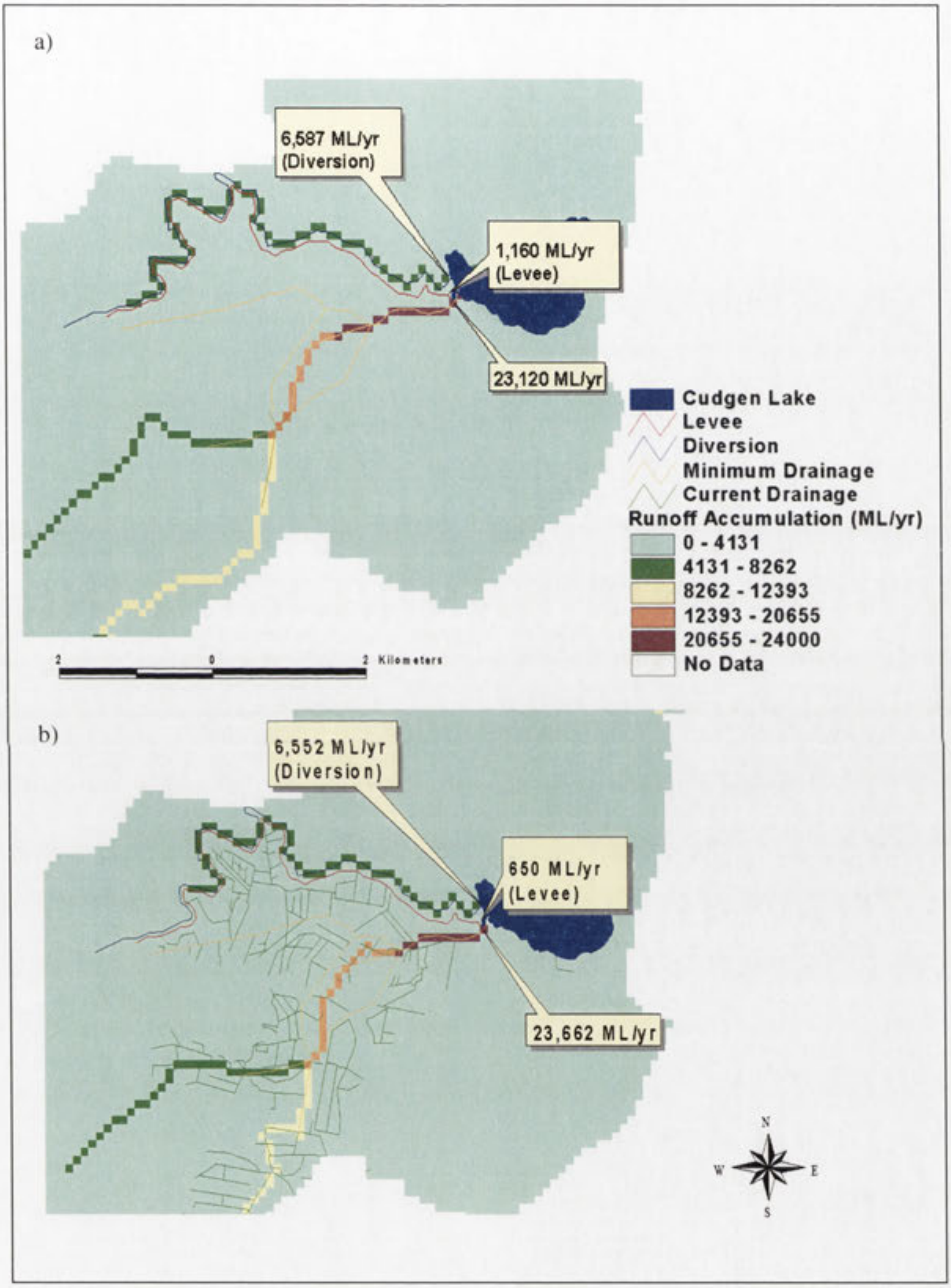


Figure 8.14 Runoff accumulation under minimum (a) and current (b) drainage with diversion channel and levee.

The combined impact of the diversion channel and the levee on surface water acid loads for both the minimum and current drainage scenarios is shown in Figure 8.12 and 8.13 respectively. Under minimum drainage, the levee bank or collection channel captures 79 tonnes of sulfuric acid per year (Figure 8.12) and 1,160 ML/yr of surface water from the floodplain (Figure 4.14a). The total amount of acid entering Cudgen Lake is 299 tonnes/yr, which includes a 2.9 tonne contribution from the diversion channel. The inclusion of a diversion channel and levee in association with minimum drainage provides a 26% annual reduction in acid load (i.e., from 404 to 299 tonnes/yr). This is in contrast to the current drainage condition in which there is only a 10% reduction in the annual load (i.e., from 404 to 370), when a diversion channel and levee are included in the model.

The diversion of upland flow from Clothiers Creek contributes to the fresh water flow entering Cudgen Lake (Figure 8.14), reducing the total annual acid concentration from around 14 mg/L to 9.7 mg/L for minimum drainage conditions and 12 mg/L under current drainage. The total amount of diverted water entering Cudgen Lake is around 6,500 ML/yr for both drainage regimes. However, the flow characteristics within the floodplain are quite different between the two regimes. The modelling shows that a greater amount of acid flow is diverted into the levee or collection channel under the influence of minimum drainage. The differences in the flow characteristics should be taken into consideration when designing containment barriers, to ensure that containment lines can cope with a variety of different flow regimes.

The diversion of upland flows from one section of the catchment will not totally alleviate the problem of increased flooding under reduced drainage conditions. The diversion of upland flow from the Clothiers Creek tributary represents less than 1/3 of the total volume of water entering the lower Cudgen floodplain and the lake. To successfully control floodwaters during periods of heavy rainfall, further diversions would be necessary if the strategy of minimum drainage is to be adopted. A further reduction is possible by diverting upland flows from the Cudgen Catchment into the neighbouring Cudgera Catchment. The floodplain region between Cudgen and Cudgera Catchments contains an area of low relief. The current drainage network directs the flow towards the Cudgen floodplain. However, it has been observed that during periods of heavy flooding some overflow into the Cudgera Catchment takes place (M.Melville, personal communication, 1999). The construction of a well-designed channel between the two catchments could be accommodated, provided there is minimal risk of acid discharge into the neighbouring catchment. Care should be taken therefore to ensure that any potential acid sulfate soils identified by the risk maps are left undisturbed and that measures, such as the construction of levee banks, are undertaken to ensure proper containment of acid surface water flows. The Christies Creek basin carries only a low to moderate environmental risk from acid sulfate soils so it is expected therefore that acid surface water loads should be fairly low.

In Chapters 4 and 5, it was identified that surface flow plays an important role in the transportation of acid to the lake environment once the acid reaches the surface waters. Unlike the Clothiers Creek diversion strategy, this new diversion strategy would not result in an increase in freshwater flow for Cudgen Lake, but should provide a reduction in the upland flow through the lower Cudgen Catchment by a further 30%. Figure 8.15 shows the current situation with one diversion and Figure 8.16 shows the effect of both diversions. From the model predictions, it is estimated that approximately 9,000 ML/yr of upland flow would pass through the Cudgera Catchment if the new diversion channel were to be adopted. This would effectively increase the discharge at Hastings Point outlet to the sea, from 22,700 ML/yr to 31,700 ML/yr (Figures 8.15 and 8.16), representing a 28 percent increase in annual flow.

While the implementation of this diversion strategy would reduce upland flows through the lower Cudgen, there is the risk that the diversion of upland flows into neighbouring catchments could result in increased flooding in areas where surface waters may normally drain quite freely. The current volume of flow modelled here for the Cudgera Catchment is low in comparison to the flows modelled for the Cudgen Catchment. Unlike the Cudgen Catchment, the flow direction paths for the Cudgera indicate a more direct flow path to the sea. Based on current flow volumes, the likelihood of increased flooding would probably be minimal. However, more work is required to determine the impacts of the additional water volumes on the hydrology of the Cudgera Catchment floodplain, as well as the added environmental problems relating to increased flow rates, such as nutrient and sediment transport. Clearly, the benefits of lessening the impacts of one environmental problem must be properly assessed against the possible adverse impacts associated with changes in floodplain hydrology. In addition, the alteration of flow paths between catchments may also prove to be very unpopular with land holders.

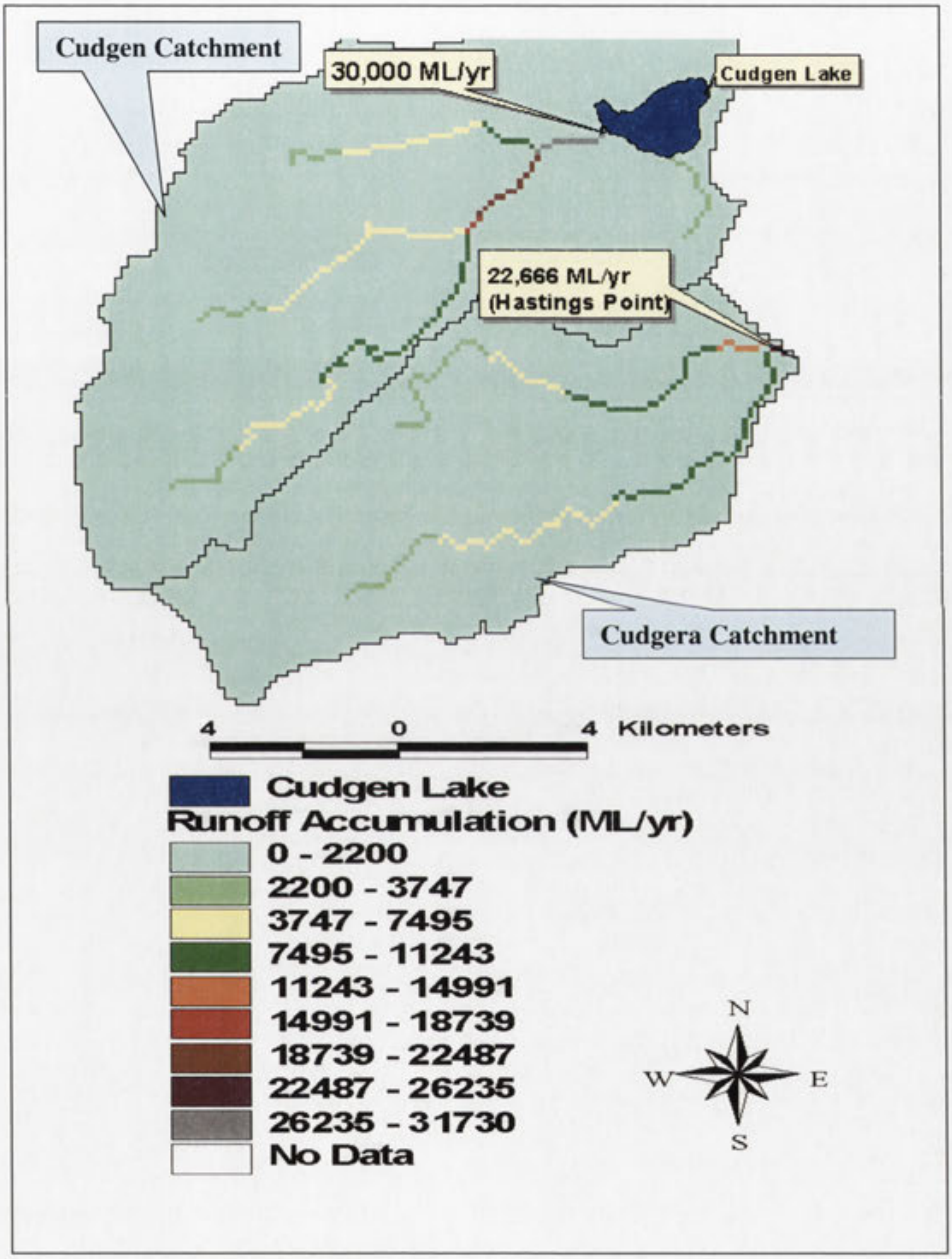


Figure 8.15 Annual runoff accumulation for Cudgen and Cudgera Catchments with no diversions. Black line indicates catchment boundaries.

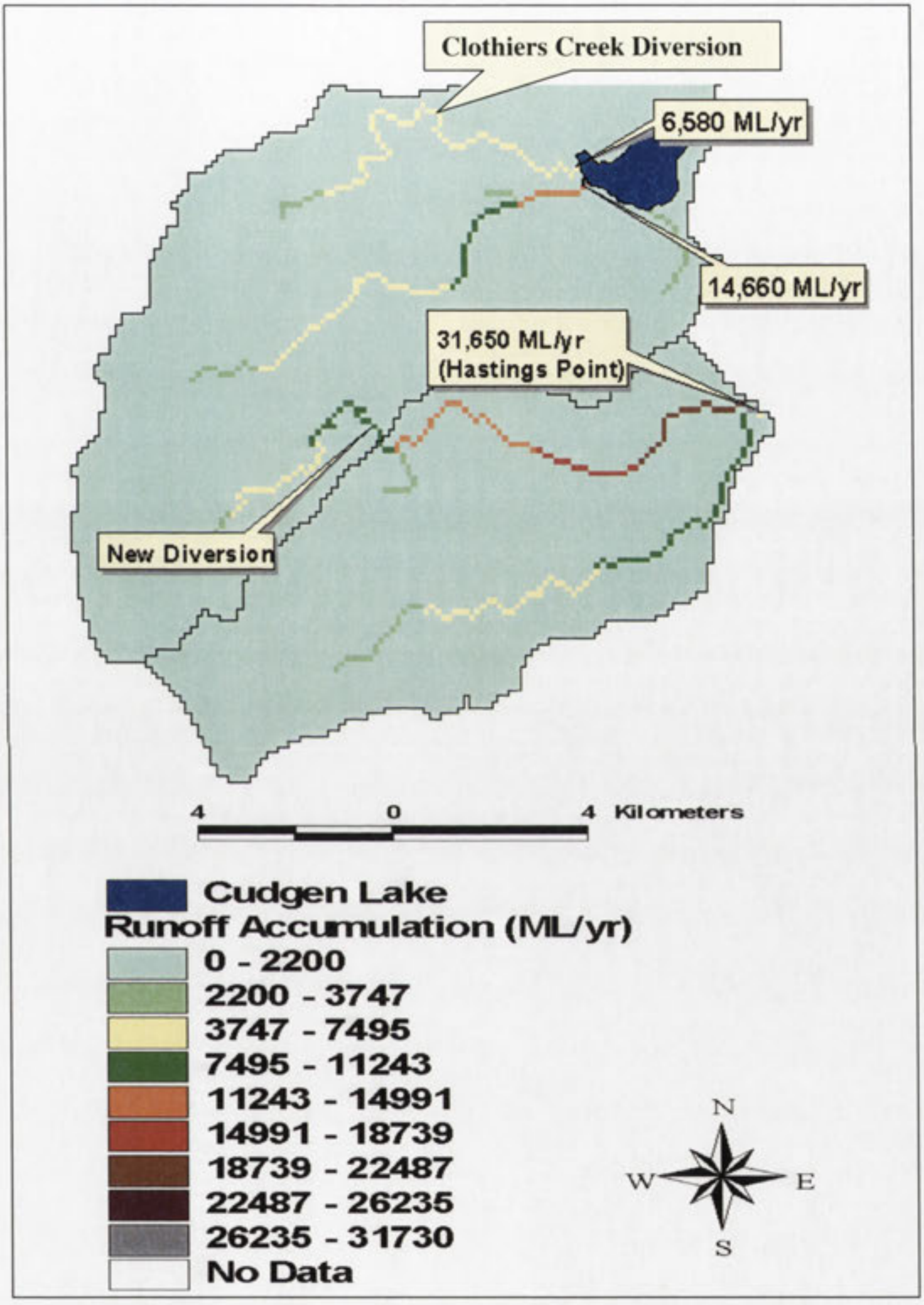


Figure 8.16 Annual runoff accumulation for Cudgen and Cudgera Catchments with diversions.

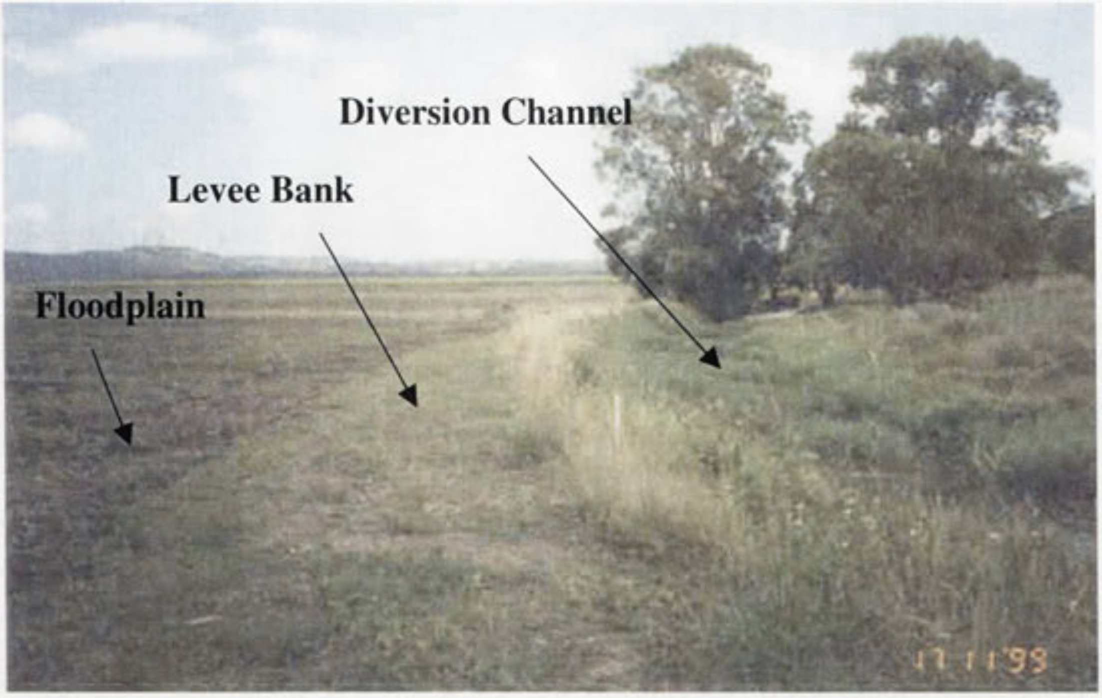


Figure 8.17 Diversion channel and levee bank, McLeods Creek.

Of course the construction of levee banks and channels to control runoff is nothing new in hydrology. Diversion channels and levee banks have been used in the McLeods Creek region to effectively divert runoff form the adjacent hills (See Figure 8.17).

8.4.3 Capping of Acid Sulfate Soils

8.4.3.1 Hydraulic and Physical Properties of Acid Sulfate Soils: Implications for Capping

Capping or encapsulation of acid soils with inert land fill, has been used in the mining industry (Murphy *et al.,* 1999; Harries, 1997; Talyor *et al.,* 1997). The same principle could easily be applied in coastal catchments containing acid sulfate soils. The use of non-acid soil as a capping material, as opposed to geotextiles or artificial barriers as used in land fill, would not only be more practical, but cost-efficient in the long run. For capping to be effective in preventing acid discharge, the capped material used should be relatively impermeable to oxygen and water, with a porosity value of less than 5% and greater than half a metre approximately in thickness (White and Melville, 1996). Porosity of the capping material may differ depending on the soil type. Compacted clays have lower porosity than sand and are therefore more suitable as a capping material. The total porosity of the capped material can be determined from the bulk density (BD) and the specific gravity (SG) of the soil particles - usually 2.6 tonnes/m^3 for soil materials. The percentage porosity of a given soil can be calculated from the following equation:

$$Porosity \quad \% = \left(\frac{1 - BD}{SG} \right) x100 \qquad 8.1$$

Many sulfidic sediments are gel like and have a volumetric water content as high as 80% (White *et al.*, 1997). They can shrink and swell under different environmental conditions (White, 2001b) creating problems for developers. The groundwater hydrology of these soils is quite different to that of non-swelling soils (Philip, 1970).

The hydraulic properties of these gel soils and the watertable position need to be taken into account if capping is to be used as a remediation strategy. Soft sulfidic sediments are particularly prone to compaction under overburden pressure. Flow and failure can often occur if surface loads such as over burden materials are applied to the soil too quickly (Smiles, 1973). Figures 8.18 and 8.19 show the consequences associated with road construction works carried out on unconsolidated sulfidic sediments in the Tweed and Cudgen Catchments. Road embankment subsidence and failure are common problems when roads are constructed on these soils. It has been reported that roads as old as 40 years in some coastal regions have settled as much as four metres (White, 2001b). In addition, the movement of soft sediments has the potential to relocate unoxidised sediments from anoxic to oxic regions resulting in the increased potential for further acidification (White *et al.*, 1997).

The consolidation and stabilisation of soft sulfidic sediments to a desired depth by de-watering is a common engineering practice used in the construction industry. The process usually involves applying a heavy load to the soil surface (Smiles and Poulos, 1969) prior to construction work. The use of vertical wick drains can enhance the de-watering (White, 2001b). The rate of de-watering depends on the hydraulic characteristics of the soil, the loading weight and the wick drainage density. Previous modelling work carried out on the consolidation of sulfidic sediments has suggested that the addition of electrolytes achieved by increasing the groundwater salt concentrations, can also increase consolidation (White *et al.*, 2001a,b; White, 2001b). However, this hypothesis requires verification through field and laboratory testing.

The process of capping effectively involves the application of a surface load to sulfidic sediments. The weight of the capped material will help consolidate soft sulfidic sediments through the de-watering process and raises the watertable above the oxidised sulfide material. Numerous authors (Smiles, 2000; Youngs and Towner, 1970; Philip, 1969a; Terzaghi, 1923) have reviewed the dynamics of water flow through swelling soils.

Figure 8.18 Road embankment subsidence on unconsolidated sulfidic sediments (White, 2001b).

Figure 8.19 Road flow caused by unconsolidated sulfidic sediments (White, 2001b).

8.4.3.2 Relationship Between Watertable Depth and Consolidation

In order to determine the optimum height of capping material, it is necessary to understand the relationship between watertable depth and the consolidation process. The following mathematical equations (8.2 and 8.3) quoted from White (2001b), provide a mathematical expression for the relationship between watertable depth and consolidation of swelling soils. The total depth of the swelling soil for a given load or watertable depth, Z_T (P^*_T, W^*, m_T) is as follows:

$$Z_T(P_T^*, W^*, m_T) = Z_T(0) - m_T B\begin{bmatrix}\left(P_T^* + W^* + 1\right)\ln\left(P_T^* + W^* + 1\right) \\ -\left(P_T^* + W^*\right)\ln\left(P_T^* + W^*\right)\end{bmatrix} \tag{8.2}$$

Where P^*_T is the imposed surface load, m_T represents the total volume of solid material in the soil profile expressed as per unit area, and W^* is the watertable depth below the soil surface in metres. Both the applied surface load and the watertable depth behave in concert with one another. Z_T (0) represents the position of the soil surface in the absence of a surface load such that:

$$Z_T(0) = m_T\left[1 + A - B\{\ln[(\gamma_s - 1)m_T] - 1\}\right] \tag{8.3}$$

The function $(\gamma_s - 1)m_T$ in equation 8.3 is the total specific volume (buoyant) of solid per unit area with γ_s the specific gravity of the soil when saturated. This function is a scaling parameter for the unloaded matrix potential and the applied surface load as well as the depth of the watertable (White, 2001b). In order to use equation 8.3, the soil moisture characteristic $V(\psi)$ of the soil must also be known. Table 8.3 compares the soil moisture parameters for two different soil types. The first is of marine origin from the Netherlands (Kim *et al.,* 1992) and the other from an estuarine origin in the McLeods Creek region of the Tweed Catchment (White *et al.*,2001b). According to White (2001b), the soil moisture characteristics of soft clay soils are well described by the equation:

$$V = A - B\ln\left|\psi\right| \tag{8.4}$$

Where (A) and (B) (see Table 8.3) are constants that describe water content at zero pressure (A) and (B) slope in equation 8.4 for a given clay matrix and temperature.

Table 8.3 Soil moisture parameters A, B and γ_s for two soil types (White et al., 2001b).

Soil	A	B	γ_s	Soil Solution
Netherlands marine origin	3.24	0.25	2.57	Seawater
Eastern Australian estuarine origin	2.32	0.30	2.55	4% Seawater

Figure 8.20 shows the modelled relationship between watertable depth and consolidation for an unloaded ($P_T = 0$) system which was calculated using equation 8.2 and the two soil types displayed in Table 8.3. In this example, the initial depth of the deposit (Z_T) is equal to 10 metres. From previous measurements by White *et al.*(2001a), there is a 2 metre saturated zone above the watertable. The effect of the watertable depth on consolidation alone is quite apparent from the modelling results.

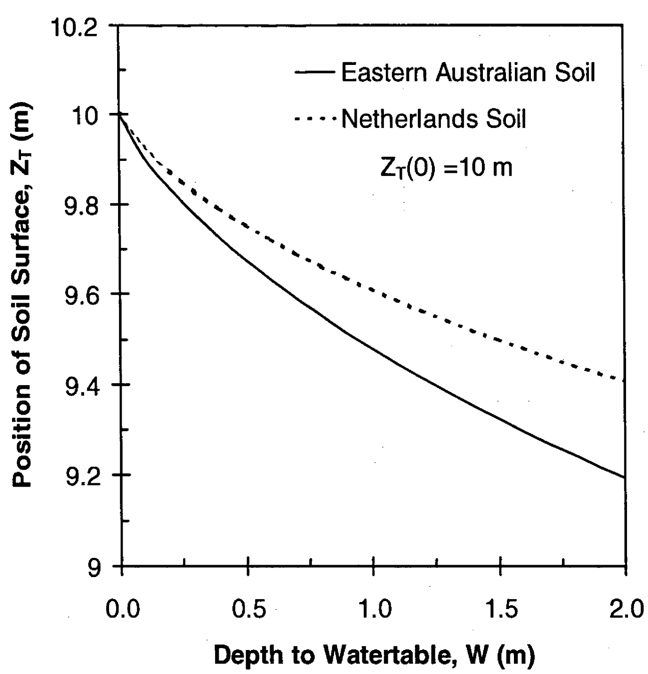


Figure 8.20 The effect of watertable depth (W) on consolidation in the absence of an applied surface load (i.e., $P_T = 0$) [White, (2000b); White et al.,2001a,b)].

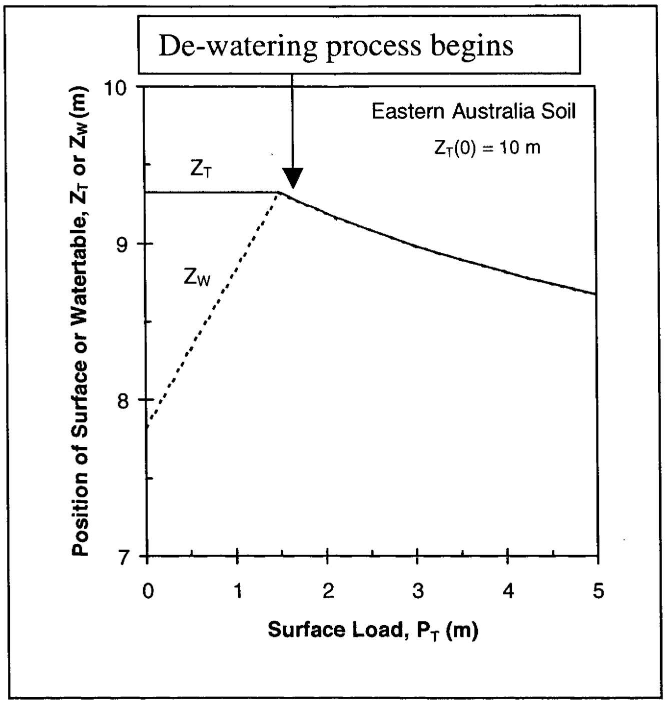


Figure 8.21 The effects of an imposed surface load on the position of the watertable height and the soil surface with the watertable initially at Z w=1.5 metre (White et al., 2001b).

Changes in air pressure can also alter the height of the watertable. Fluctuations in the watertable resulting from changes in the atmospheric conditions can be as high as 0.2 metres (White *et al.,* 2001a). However, according to Philip (1969b), for a closed system, a rise in the watertable level is proportional to the weight of the imposed surface material P_T. The modelled impact of an applied surface load on the position of the watertable and the soil surface is shown in Figure 8.21. According to these results, as soon as the watertable reaches the soil surface, consolidation then takes place and de-watering begins. For an initial watertable height (Zw) of 1.5 metres below the soil surface, the consolidation process commences when a 1.5 metre load is applied to the soil surface.

Since the applied load of 1.5 metres modelled here represents water, which has a lower density than a solid material such as clay, it is possible to have an overall height of less than 1.5 metres. As mentioned previously, capping is only effective when the capped material is greater than 0.5 metres in height (White and Melville, 1996). Therefore, the ideal range is between 0.5 and 1.5 metres.

The ideal height H_T of the capping material can be derived from:

$$H_T = P_T \Big/ D_{solid} \; / \; D_{water} \qquad (8.5)$$

Where P_T is equal to the height of the applied surface load (water) which according to the modelling results is 1.5 metres, D_{solid} is the density of the capping material and D_{water} is the density of the water. The density of water is 1t/m^3 and the density of clay is around 1.9t/m^3, which gives an overall capping height (H_T) of 0.79 metres.

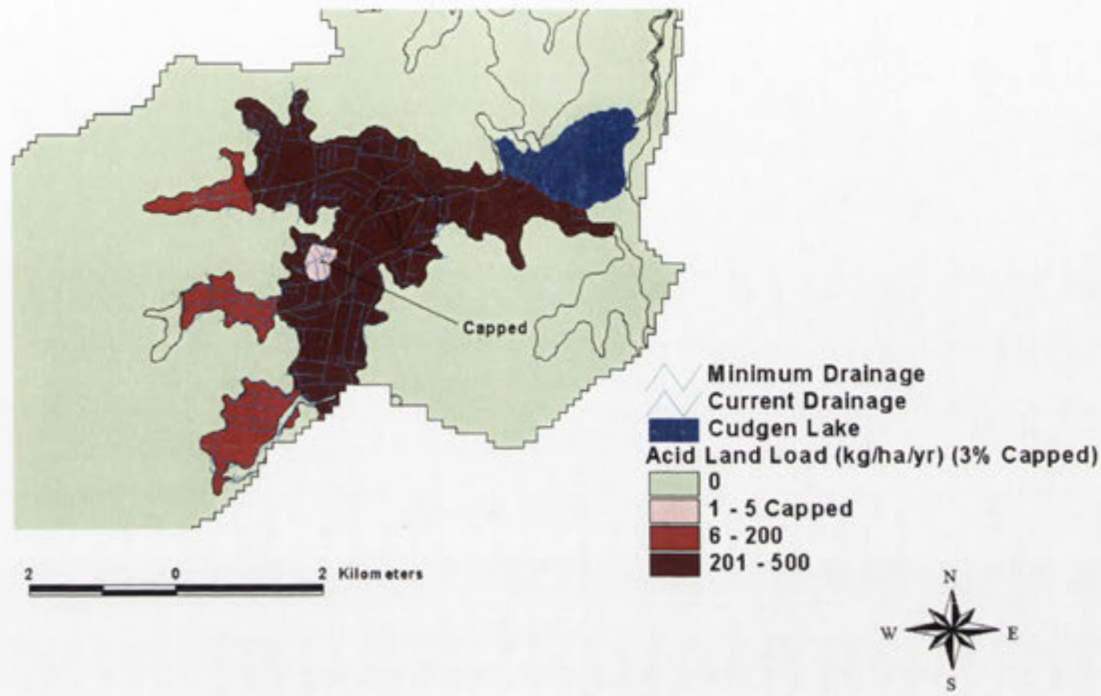
The application of a surface load of 0.8 metres will initially result in some acid discharge, as acid water is slowly leached out of the soil through the de-watering process. During this stage it is important to contain and treat the leachate by the addition of lime or some other neutralising agent. Once the de-watering process is completed there should be a cessation in discharge. The process of consolidation effectively reduces the capacity of the soil to hold and absorb water and therefore contributes to a reduction in acid discharge following periods of heavy rainfall.

8.4.3.3 Modelling the Impact of Capping on Acid Surface Water Loads

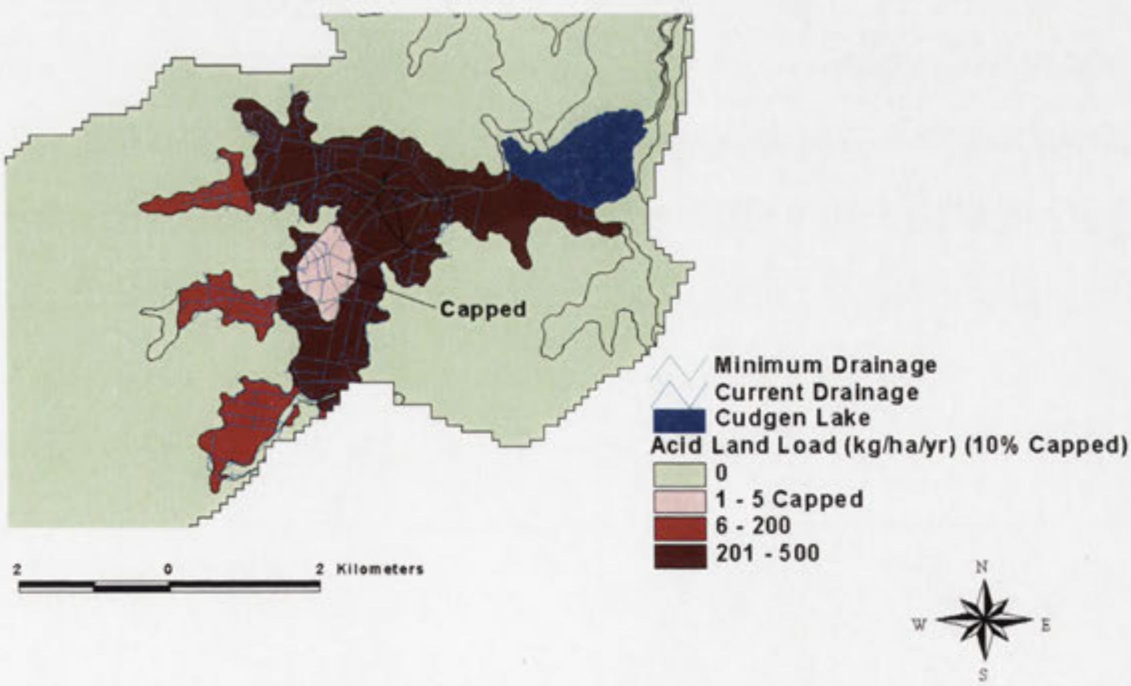
From a water quality perspective, what is uncertain about the effectiveness of capping is the extent to which capping can significantly reduce acid loads. Capping all acid sulfate soil high risk areas is simply not feasible due to the large areas involved and the cost of capping (~$AUD 10-20/m^3)(M Tunks, personal communication, 2001). There is the added problem of ensuring that land holder's interests are adequately addressed. Normally, it is only feasible to cap scalded areas (White, personal communication, 2001).

Here, the impact of capping on acid discharge was modelled. A range (3-34%) of capping scenarios was examined and the spatial distribution of these capped regions is shown in Figure 8.22. Some lateral movement of acid into the drainage network might still be expected with an estimated discharge of between 1-2%. For this reason an acid land loading of 5 kg/ha/yr was assigned to the capped regions represented in the model. The sulfuric acid surface water loads for 3, 10, 17 and 34 % capping regimes under minimum and current drainage scenarios is shown in Figures 8.23, 8.24, 8.25 and 8.26 respectively.

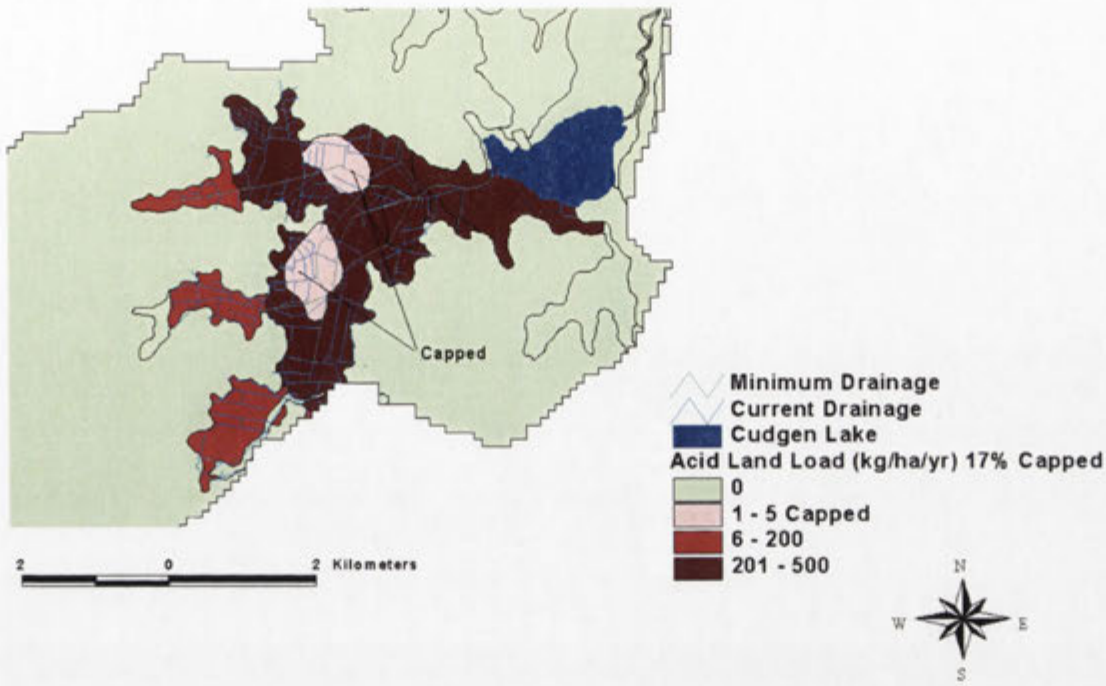
Figure 8.22 Capping regimes used in the modelling.



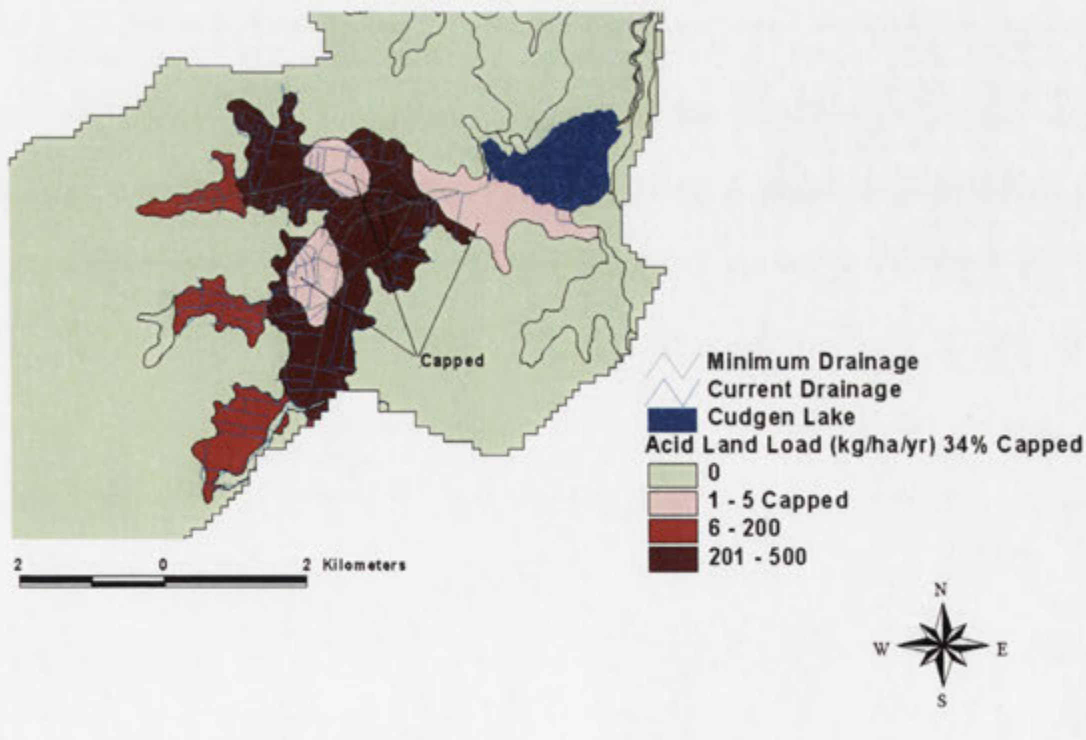
3% Capped



10% Capped



17% capped



34% Capped

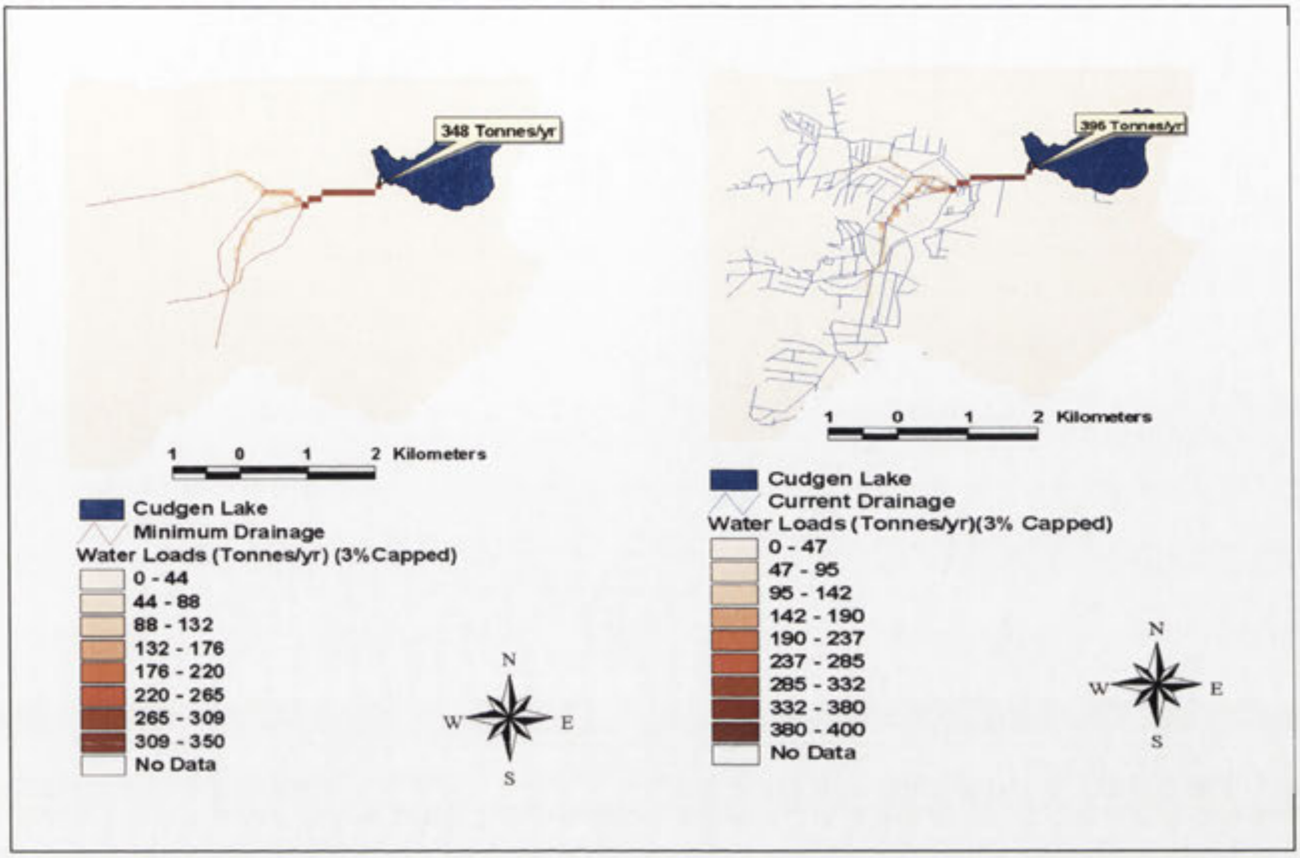


Figure 8.23: 3% capped with minimum (left) and current drainage (right).

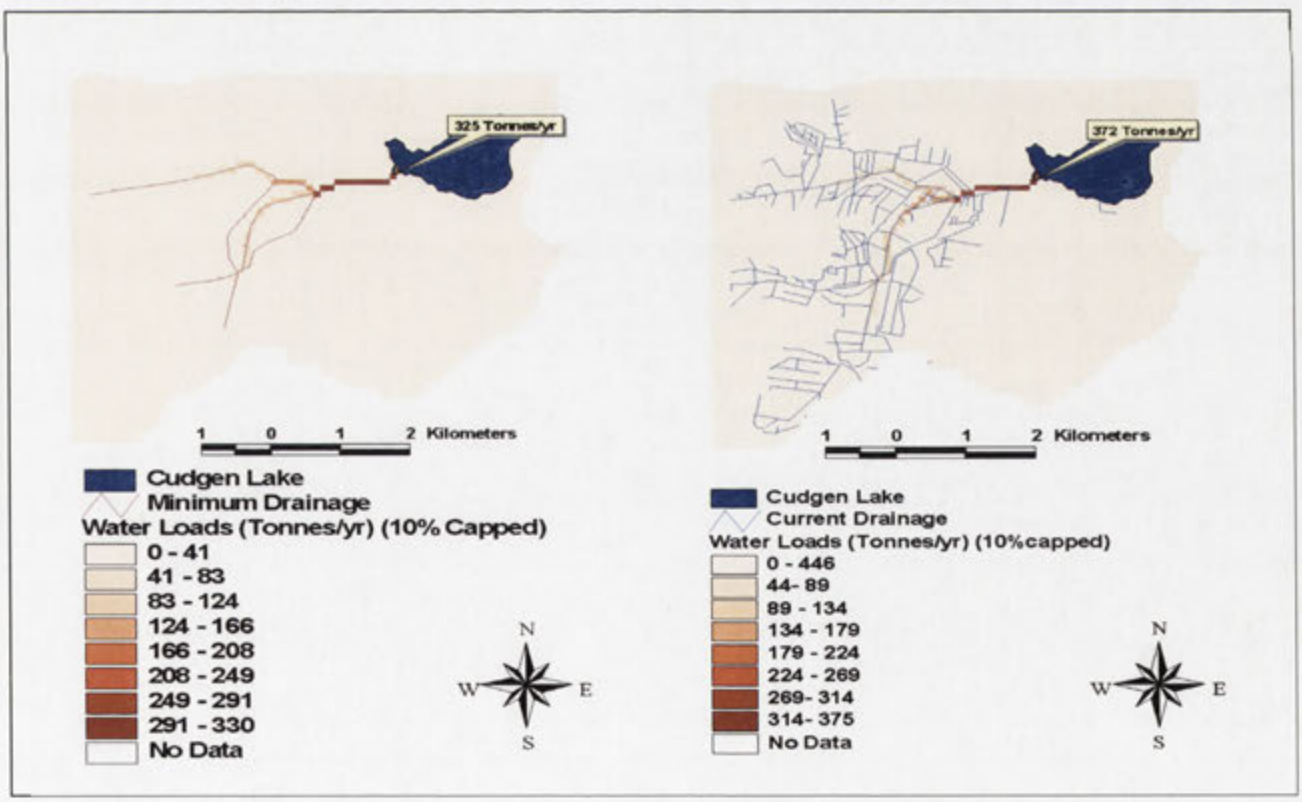


Figure 8.24: 10% capped with minimum (left) and current drainage (right).

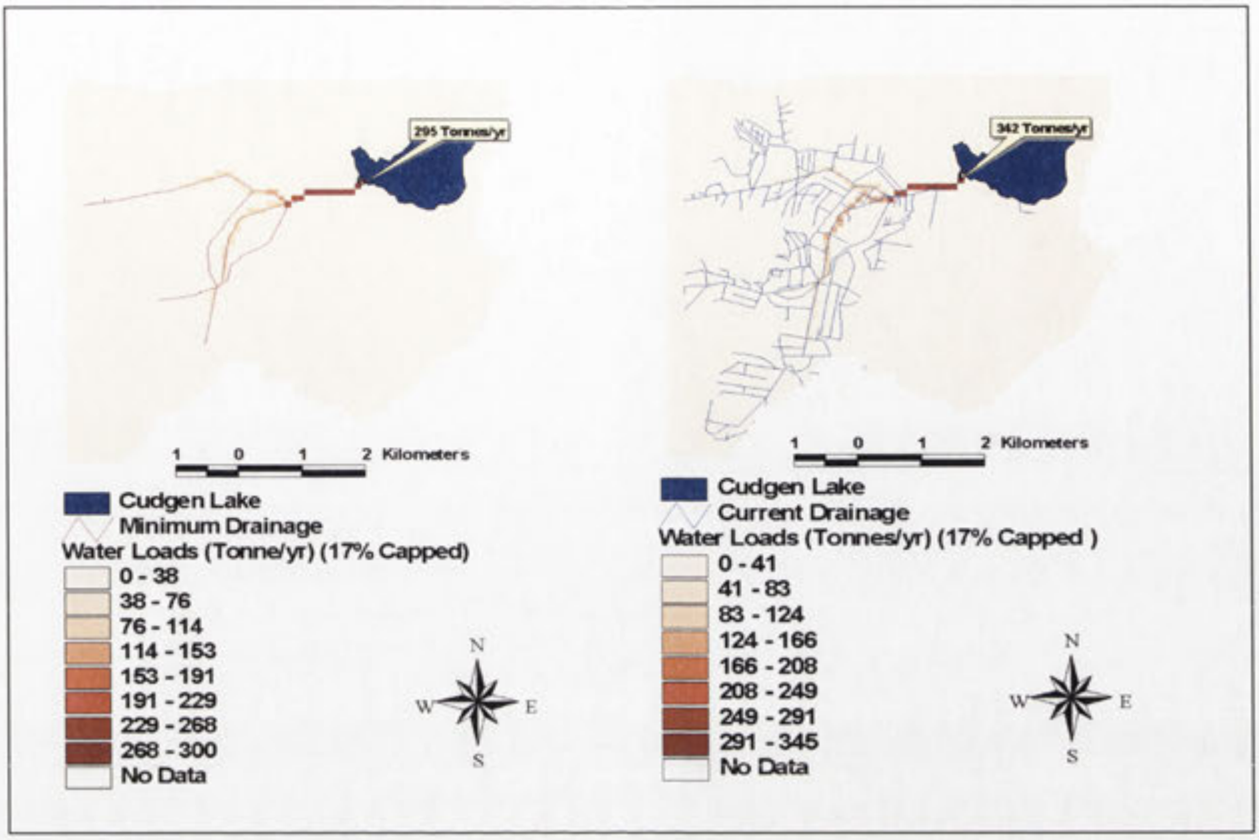


Figure 8.25: 17% capped with minimum (left) and current drainage (right).

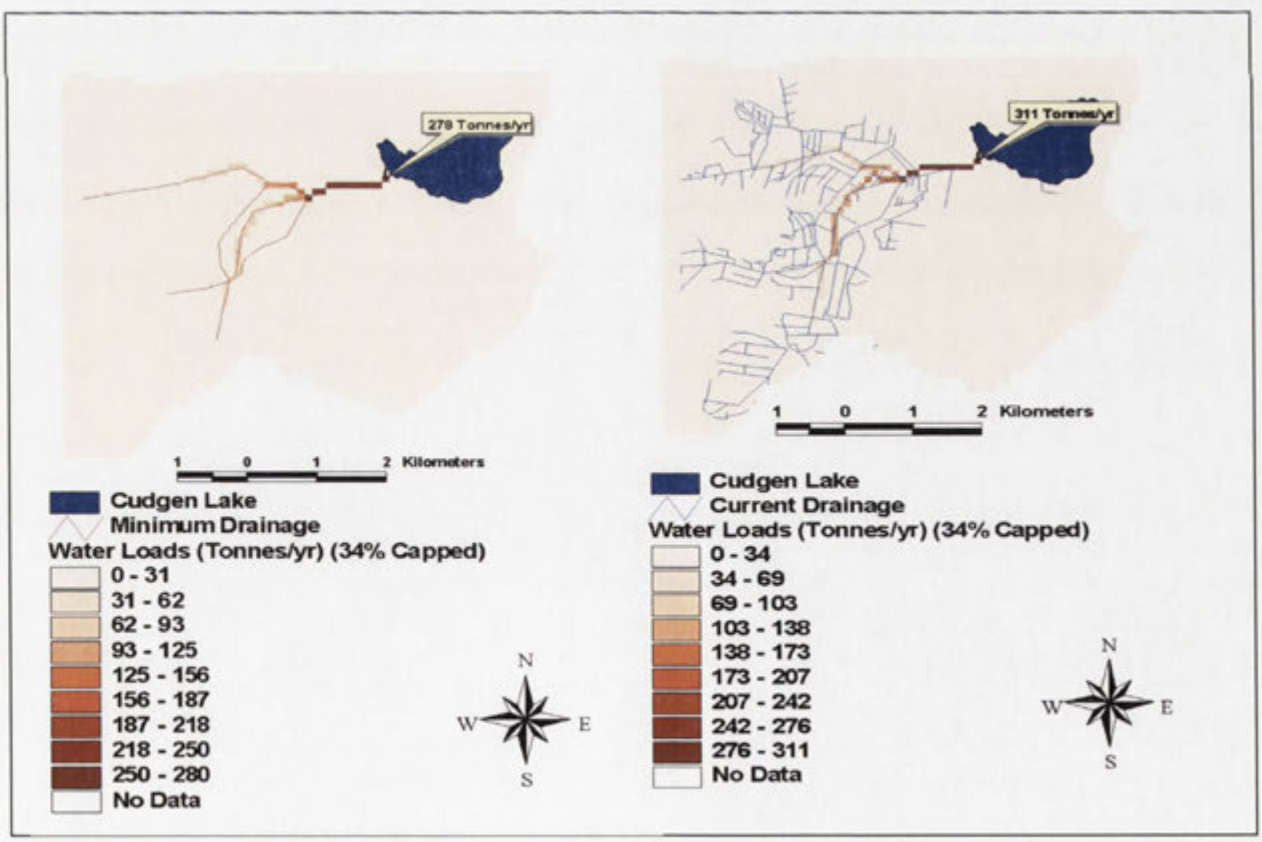


Figure 8.26: 34% capped with minimum (left) and current drainage (right).

Table 8.4 Percentage reduction in sulfuric acid surface water loads under a range of capping regimes.

Capping regime	Minimum drainage	Current drainage
34%	*32%*	*23%*
17%	*27%*	*16%*
10%	*20%*	*9%*
3%	*14%*	*3%*

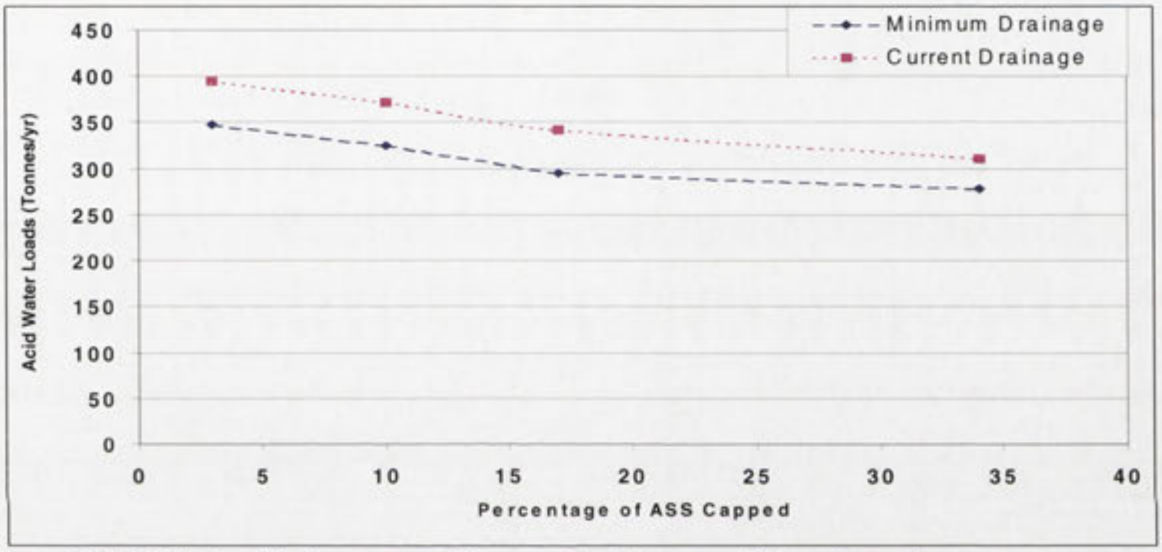


Figure 8.27 Relationship between acid water loads (tonnes/yr) and capping.

The percentage reduction in sulfuric acid surface water load using a combination of capping regimes is shown in Table 8.4. The results show that, under current drainage, a 23% reduction in sulfuric acid surface water load can be achieved if 34% of the acid sulfate soil region is capped. The modelling results also indicate that there is an almost linear relationship between the percentage of the floodplain that is capped and the water loads entering the lake (Figure 8.27). However, on closer examination the effectiveness of capping is slightly diminished in the case of minimum drainage scenario as the percentage of capped land is increased from 17% to 34 %. The reason for this is more than likely attributed to a spatial phenomenon in which the capped material has no real significant impact on preventing further discharge in regions where the acid surface water loads are already well contained within the floodplain area (See Figures 8.2-8.6). This would include the foreshores and region immediately to the south west of Cudgen Lake. This region is identified from the geomorphology data as estuarine sandplain (Table 5.3, Section 5.3.3.2) or backswamp with few natural or man-made drainage lines. From field observations, this area also contains very soft sulfidic muds which hinders walking and driving activities, even during dry periods. The application of overburden in regions where the geomorphology makes access difficult may prove to be extremely costly and impractical.

8.4.3.4 Impact of Roadway Development

Section 8.4.3.1 examined the hydraulic and physical properties of acid sulfate soils and the problems these soils pose during construction works. The Pacific Highway Yelgun to Chinderah Upgrade began during August 2000. Because this 23 km stretch of road crosses several floodplains including the lower Cudgen (Figure 8.28a & b), a detailed acid sulfate soils management plan was adopted prior to construction works (EIS, 1998; Cramer *et al.*,2002). Since considerable overburden material was used in the construction of the dual carriageway, some of the pre-construction requirements were applied to this roadway project, including the process of de-watering as discussed in section 8.4.3.2. In addition, around 70,000 m^3 of ASS was removed and treated during construction (Cramer *et al.,* 2002).

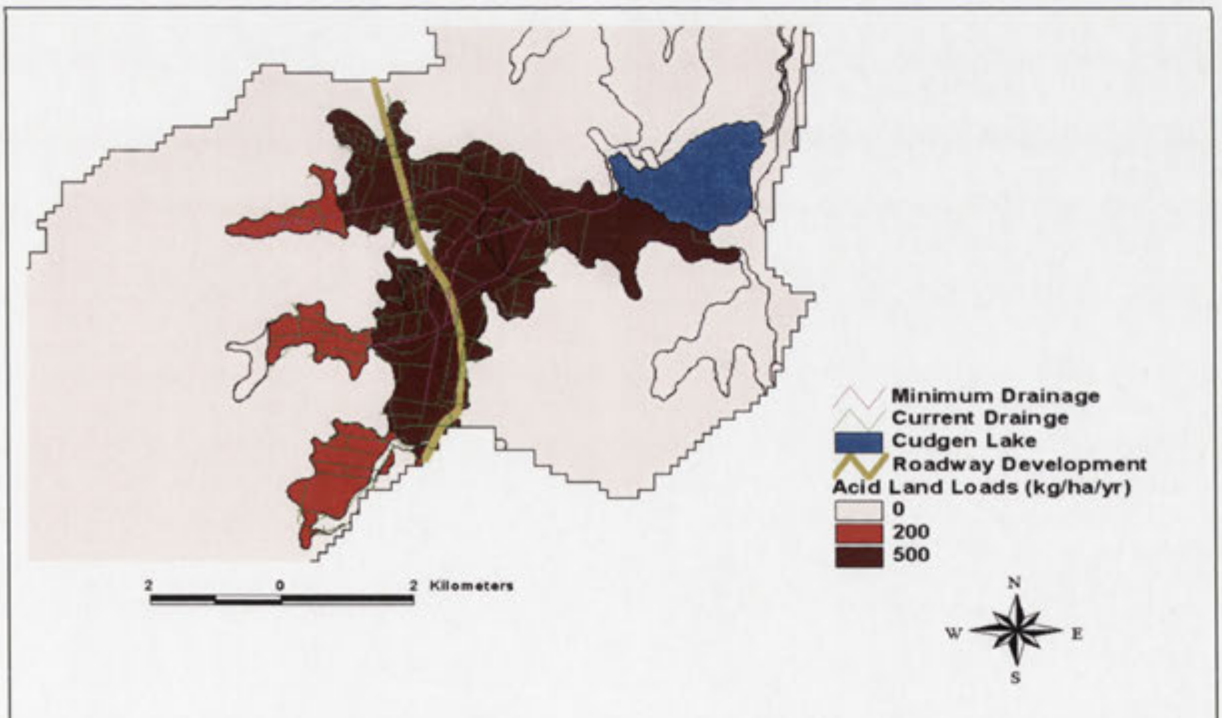


Figure 8.28a The Yelgun to Chinderah roadway of the Pacific Highway development, passes through ASS high risk areas of the Cudgen floodplain.

Figure 8.28 b. The completed roadway passes through the lower Cudgen floodplain.

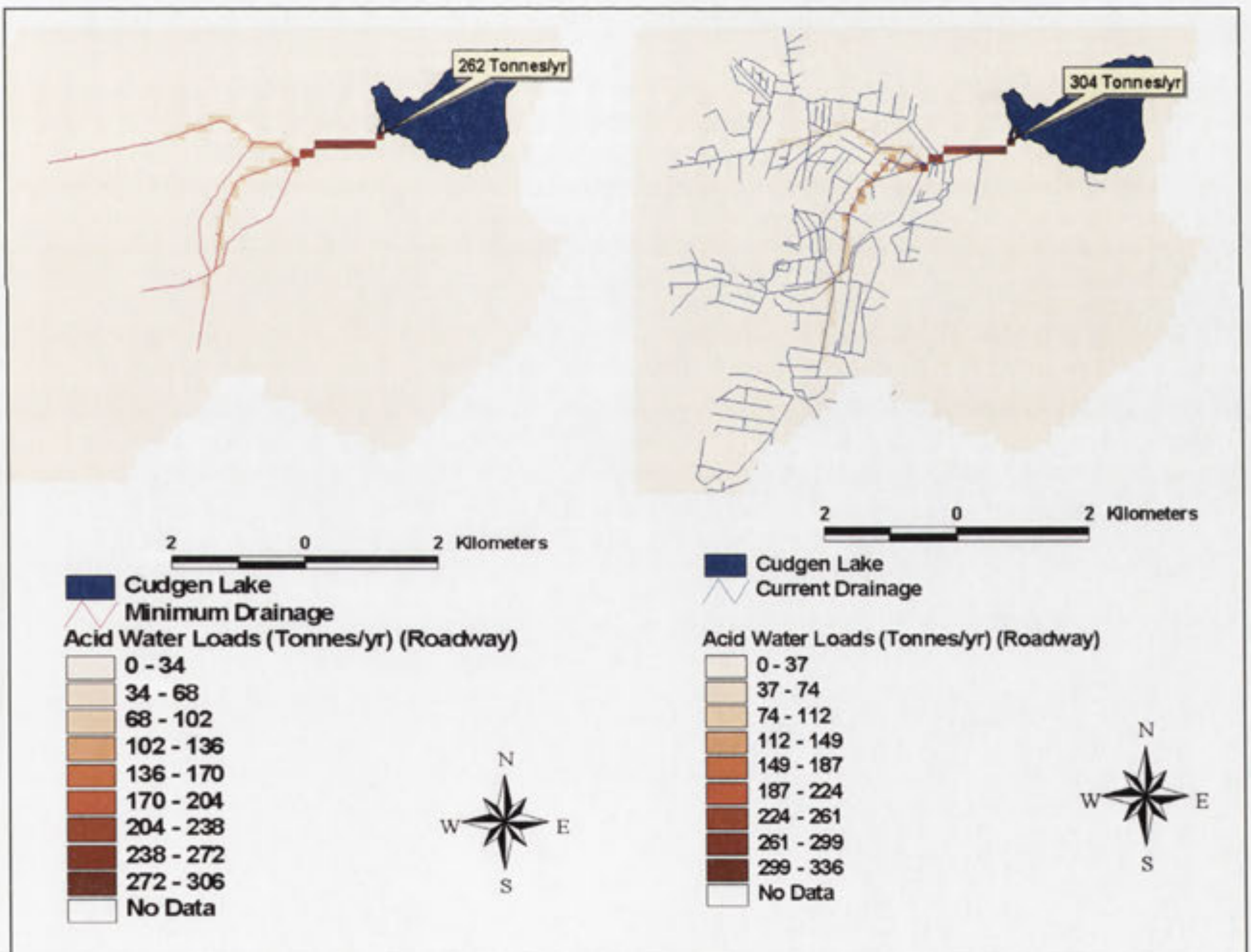


Figure 8.29 Possible impact of the Yelgun to Chinderah Pacific Highway Upgrade on acid surface water loads in tonnes of sulfuric acid.

We do not often associate large development projects such as the Yelgun to Chinderah Pacific Highway Upgrade as a remediation strategy. However, this project has effectively treated around 225 hectares of acid sulfate soils or 30% of the lower Cudgen floodplain. According to the results presented in Figure 8.29, the roadway development has the potential to reduce acid surface water loads by as much as one third under current drainage conditions.

This project is a good example of how the development of an acid sulfate soils management plan involving all stakeholders was accomplished without compromising construction deadlines. Unfortunately, post-construction works such as drainage design and the implementation of continuous monitoring programs have taken longer to initiate. These activities are planned for the future as part of the ASS Hot Spots Remediation program through the implementation of the "Cudgen Lake Catchment ASS Hotspot Long-term Management Concept Plan" (TSC, 2001). The hydrological water quality GIS model, developed as part of this thesis, is an integral component of this plan.

8.4.3.5. Implications of Capping as a Remediation Strategy

There are a few factors that need to be considered if the capping of selected acid sulfate soil areas is to be used as a suitable remediation strategy. These include:

(1) The geomorphology of the floodplain,
(2) The weight and height of capped material used relative to the watertable height,
(3) The need to treat acid leachate originating from the de-watering process,
(4) The cost associated with the capping and transport,
(5) Availability of capped material and ease of access.

Clearly, capping configurations will differ from one catchment to the next given the variability in both terrain and geomorphology between catchments. Watertable elevations may also vary somewhat between catchments. Careful consideration should also be given to development projects, such as the Yelgun to Chinderah Pacific Highway Upgrade, that might offer some long-term advantage in reducing acid discharge.

8.4.4 The Effects of Tidal Flushing on Cudgen Lake

The tidal characteristics of Cudgen Lake were briefly discussed in section 5.3.5, Chapter 5. Tidal studies have shown Cudgen Lake to be weakly tidal (WBM Oceanics Australia, 1980). WBM Oceanics Australia (1998) modelled the effects of dredging on tidal exchange and its long-term impact on flooding. The modelling concluded that dredging the entrance to Cudgen Lake from Cudgen Creek to 0.7 AHD and deepening the first 50 metres of Cudgen Creek to –1.0 metre ADH, had no significant impact on additional flow capacity, when compared to the total flow capacity created by the floodplain. This particular type of dredging would have no noticeable impact on the tidal range or on tidal flushing. Dredging Cudgen Creek from the entrance of Cudgen Lake through to the ocean to a width of 10 metres at –1.5 metre ADH increased the flow area from 4 m^2 to 15 m^2. This massive excavation increased the tidal range by up to 7 centimetres with only a slight improvement in tidal flushing.

The dredging of Cudgen Creek has important environmental implications in terms of water quality. Geomorphology map data (Table 5.3, Section 5.3.3.2) indicate that the entrance to Cudgen Lake and the embankment of Cudgen Creek, is identified as estuarine and aeolian sand plains containing PASS and carries a moderate to high environmental risk (Figure 5.8, Chapter 5, p128) of releasing more acid into the environment if disturbed through dredging activities. There is also evidence to suggest that the opening of coastal lakes to the sea for fish recruitment can lead to the destruction of riparian and wetlands habitats (Wilson *et al.*, 2002). The Healthy Rivers Commission Inquiry into Coastal Lakes (HRC, 2002) has stressed that the artificial opening of coastal lakes is of major concern with respect to the health of these coastal systems.

Dredging has previously been undertaken at various times in some sections of Cudgen Creek to improve tidal exchange. However, these activities have proven to be ineffective in neutralising acid discharge from large outflow events. Furthermore, around 30 hectares to the north of the lake, including Cudgen Creek, is classified as natural wetland under SEPP 14, which prohibits clearing, drain construction or any other type of development proposal without approval from the then NSW Director of Urban Affairs and Planning (WBM Oceanics Australia, 1998).

8.4.5 Surface Water Volumes in Cane Fields

The physical properties of the soil and the topography of the land are important factors that regulate surface and groundwater flows. Anecdotal reports have suggested that small changes in the topography at the floodplain or field level can affect both surface drainage and groundwater hydrology, reducing acid outflow events by up to 80% (ASSMAC, 1999b). The mean residence time T for an unsaturated soil-water store ΔS_t and recharge rate R is given by

$$T = \Delta S_t / R \qquad 8.6$$

In coastal areas where rainfall is high and watertables are shallow, the residence time can be from one to five days, if ΔS_t is 50mm and R is 10 to 50 mm/d (White *et al.*, 1993).

The application of laser levelling of cane fields in the McLeods Creek region has improved surface drainage, thereby reducing infiltration and groundwater recharge (White *et al.*, 1999a). To the naked eye, non-levelled cane blocks appear flat (Figure 8.30) but contain depressions that collect surface water following periods of heavy rainfall resulting in localised water logging. Laser levelled fields produce healthier crops and there are no signs of water logging following heavy rainfall (R Quirk, personal communication, 2001).

A detailed ground survey can provide the necessary elevation data to create a DEM representing the topographical features of a cane block. From a DEM it is possible to derive a quantitative measure of the volume of surface water that is captured by a cane block that has not been laser levelled. The results obtained from this quantitative determination can then be used to estimate the amount of infiltration from a typical non-laser levelled block. The impact of furrows on infiltration was also examined.

The DEMs generated in the previous chapters were derived from cartographic data sources which are readily obtainable in the form of contour maps or from aerial photography. DEMs derived from ground surveys usually require more time and effort in collecting the data and presenting it in a suitably digitised format; however, they often display finer topographical detail together with higher spatial resolutions (i.e., 1-50 metres). A DEM which accurately represents the geographical features of a cane block with an average surface area of around $1500m^2$, should ideally have horizontal spatial resolutions between one to two metres (Hutchinson, personal communication, 2000).

Figure 8.30. Non-laser levelled cane block used in this study.

8.4.5.1 Ground Surveying and Data Collection

Ground surveying was conducted on two non-laser levelled cane blocks within the McLeods Creek region. The McLeods Creek floodplain has numerous cane blocks separated by drainage lines. The drainage features of the McLeods Creek region was previously shown in Figure 4.38 in Chapter 4, p110. The cane blocks chosen were partly prone to water logging problems and were due for laser levelling during 2002 (R. Quirk, personal communication, 2001). Data acquisition for the DEM involved surveying each block for elevation above Australian Height Datum (AHD) in 10 metre transects. Geographic coordinates, measured in UTM, for all the cane blocks within the McLeods Creek region were previously derived using GPS and provided by the Condong Sugar Mill Cooperative. Temporal Bench Marks (TBM) were established from known Permanent Bench Marks (PBM) within 10 metres of the two study sites. A series of TBMs were evenly placed along the front of each block at a distance of 10 metres. For the second cane block, TBMs were every 7.5 metres. An elevation (z) was determined for each 10 metre point on the transect line and an ASCII file containing z, x and y coordinates for each point was created.

8.4.5.2. Creation of a Digital Elevation Model from Ground Survey Results

The ANUDEM program was used to generate a one metre DEM, with grid cells of 1 m^2 , from the surveyed point data in ASCII file format. For this analysis, it was necessary to identify sinks in the DEM. A sink indicates a depression within the surface of the field, which collects surface water. ANUDEM automatically removes sinks where possible within the DEM due to a global drainage enforcement algorithm. To prevent ANUDEM from automatically removing sinks in the DEM, the global drainage enforcement algorithm was not used. The DEM for both fields is shown in Figure 8.31.

The surface area and volume for each depression was estimated from the command function "fill" in ArcInfo (version 8.02). The "fill" command produced a second DEM with the sinks filled in. The subtraction of this filled DEM from the unfilled DEM generated a third DEM showing the sinks only (Figure 8.32). This third DEM or sink DEM was used to derive the surface area and volume of the field depressions. The surface area and volume for all field depressions were determined using two methods. The first involved using the Arcview command "summarise zones" to derive an estimation of the volume and surface area for each sink in the DEM. The second method used the 3D Analyst extension in Arcview (version 3.2) to convert the DEM to a Triangular Irregular Network (TIN)(see section 3.3, Chapter 3). This conversion creates a three dimensional structure of the surface of the cane blocks as shown in Figures 8.33b and 8.34b.

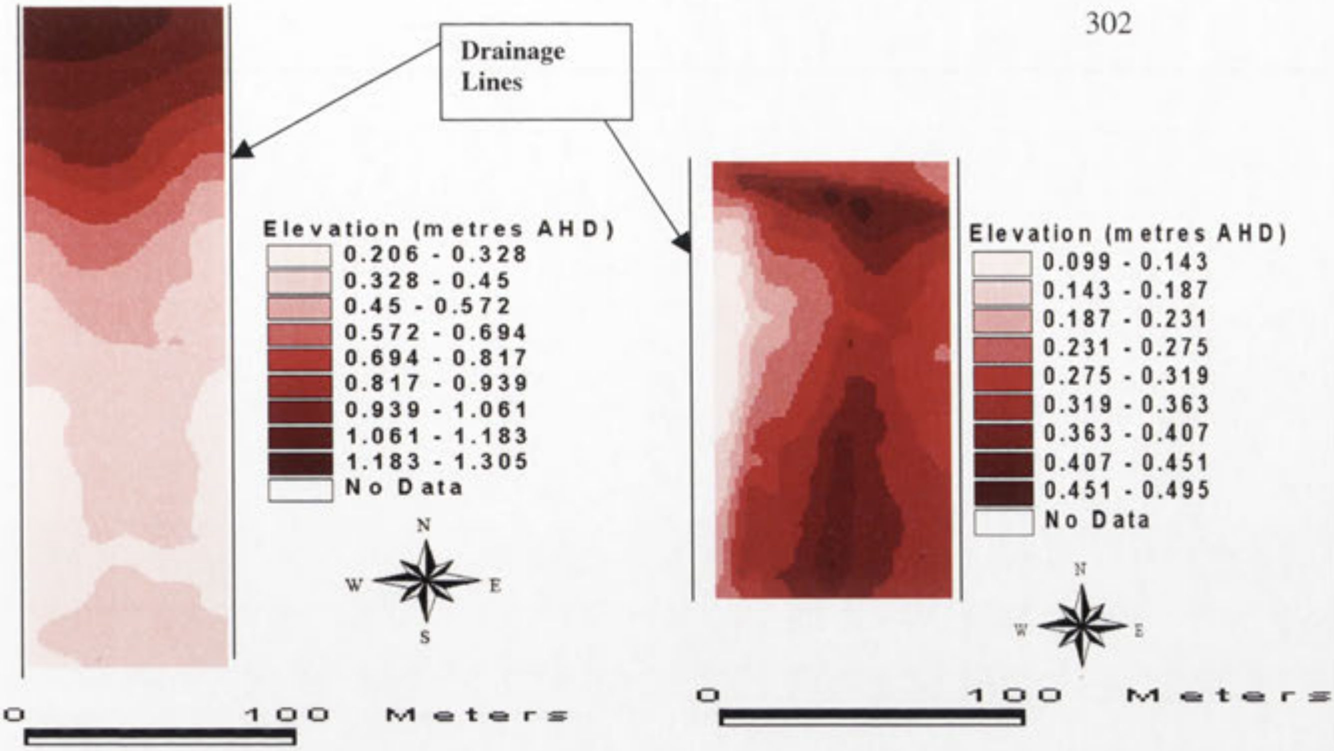


Figure 8.31 DEM of cane block 1(left) and cane block 2 (right).

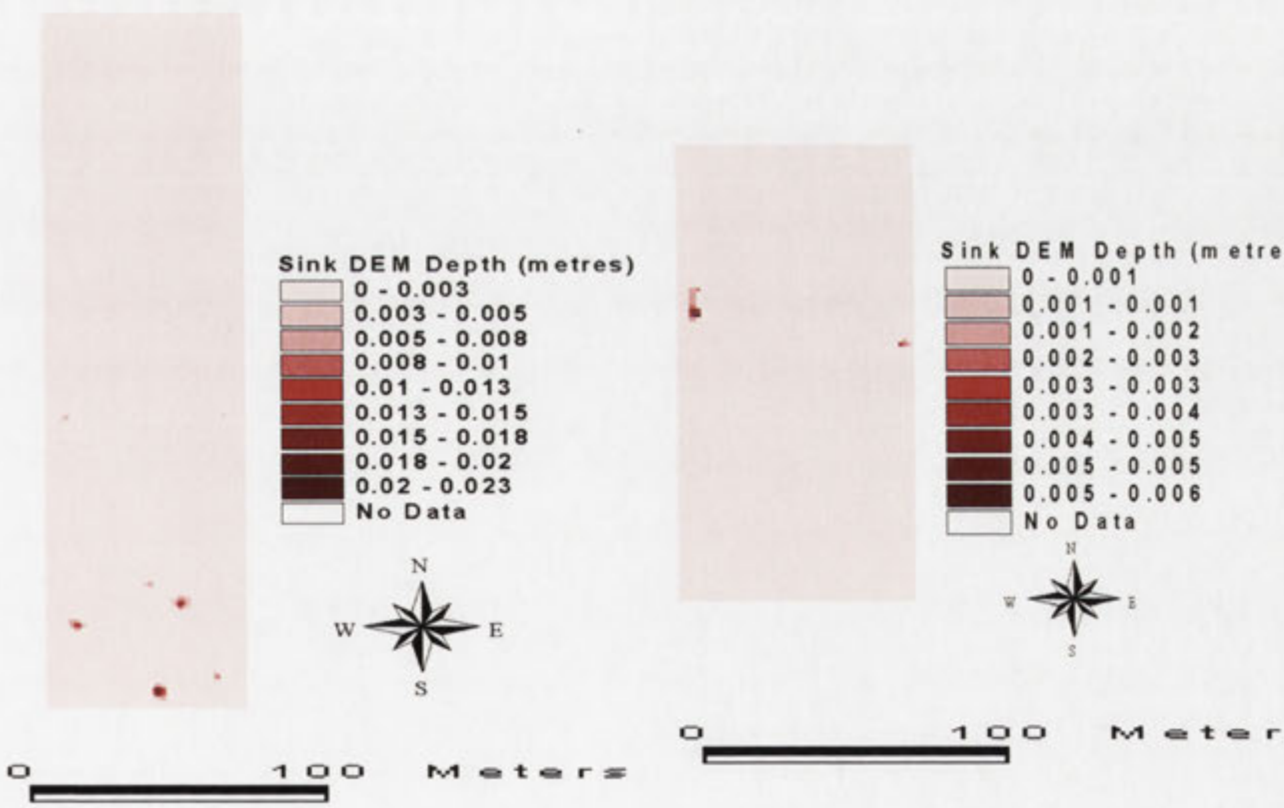
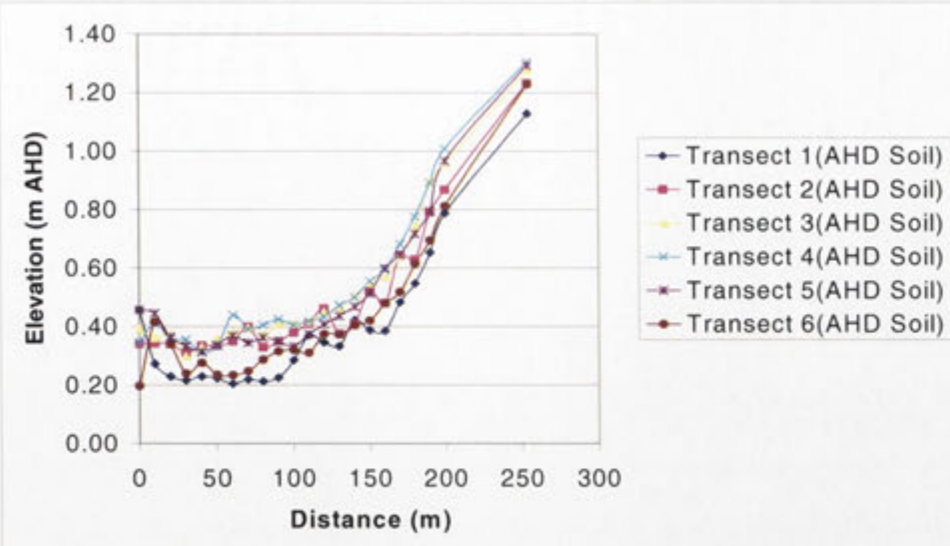
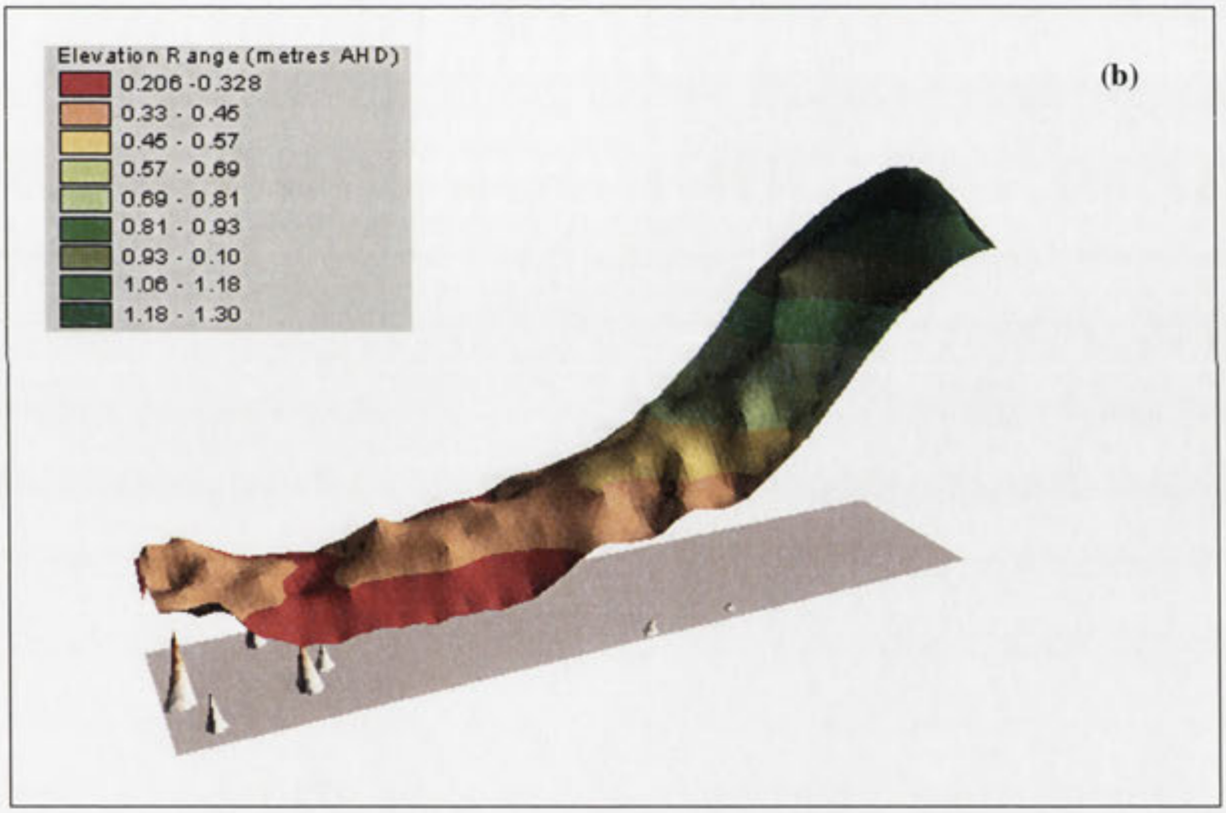


Figure 8.32 DEM of sinks in cane block 1 (left) and cane block 2 (right).

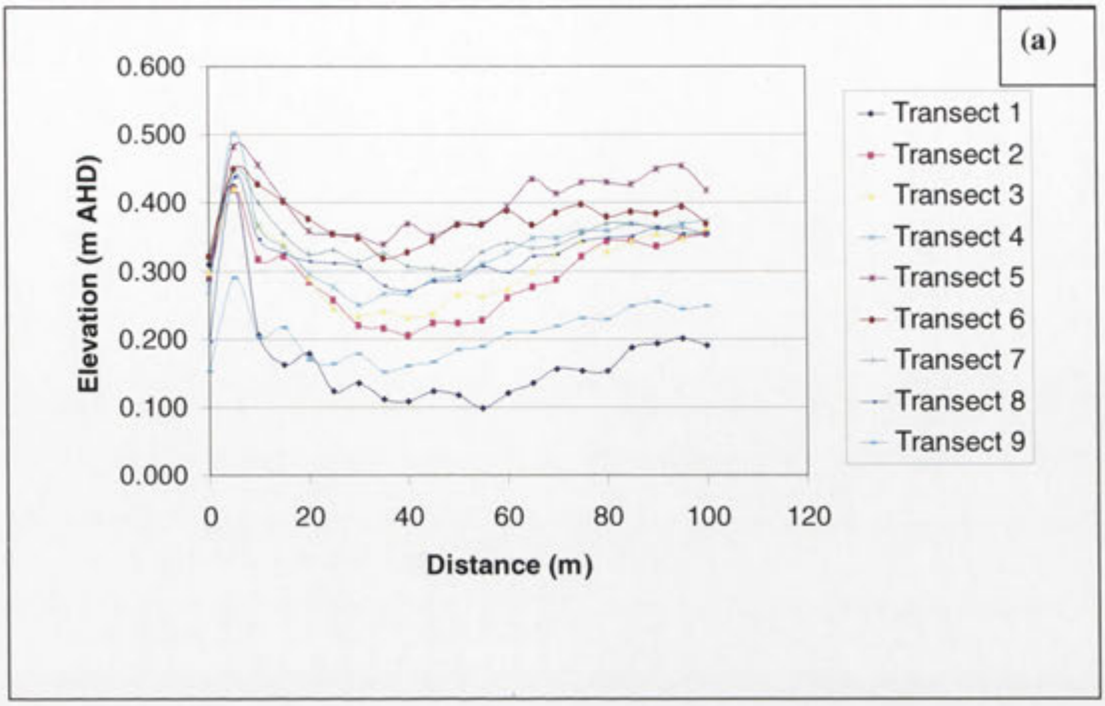


(a)



(b)

Figure 8.33. Top graph (a) shows the transect points used to generate the DEM. (b) 3D profile of block 1(top plane) produced from a TIN exaggerated 100 times. Sinks displayed as the inverse of the 3D view exaggerated 100 times (bottom plane). The same block is photographed in Figure 8.30.



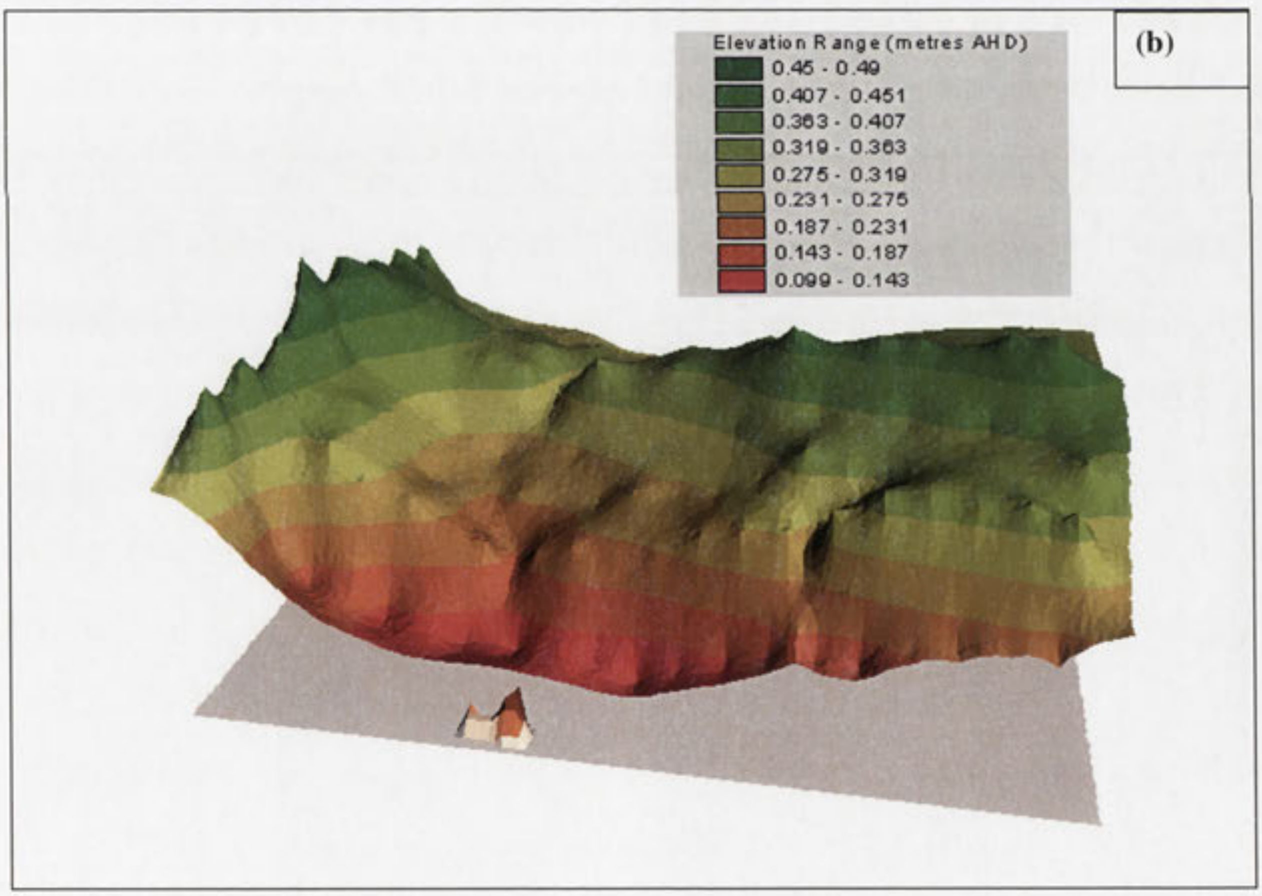


Figure 8.34. (a) Top graph shows the transect points used to generate the DEM. (b) 3D profile of block 2(top plane) produced from a TIN exaggerated 100 times. Sinks displayed as the inverse of the 3D view exaggerated 100 times (bottom plane).

Table 8.5 Sink characteristics for cane block 1.

Sink Characteristics	Result
Maximum Sink Depth	0.023 m
Planimetric Area of Sinks	245.5 m ^{2}
Surface Area of Sinks	245.6 m ^{2}
Volume (determined from DEM)	0.88m^3
Volume (determined from TIN)	0.83 m^3
Number of Sinks	6
Total Area of Cane Block	15,000m^3

Table 8.5 summarises the results obtained from the analysis of the DEM and TIN for cane block 1. ANUDEM identified a total of six sinks in the DEM for cane block 1. There was very little difference in the total sink volume obtained using the two methods, which indicates that the volume of surface water can be determined either from the DEM or from the TIN shown in Figures 8.33 and 8.34. However, to estimate the planimetric and surface area for all sinks in the DEM it is important to display the DEM in three-dimensional view. For this reason it was necessary to convert the DEM into a TIN. As shown in Table 8.5, there is less than one square metre difference between the planimetric area and the surface area, which indicates that the depressions in the cane block were shallow. The maximum depth across all the sinks was 0.023 metres.

Table 8.6 Sink characteristics for cane block 2.

Sink Characteristics	Result
Maximum Sink Depth	0.006
Planimetric Area	62.500 m^2
Surface Area	62.502 m^2
Volume (determined from DEM)	0.079 m ^{3}
Volume (determined from TIN)	0.088 m ^{3}
Number of Sinks	2
Total Area of Cane Block	6,000m^2

A similar result was obtained for the second cane block (Table 8.6). Only two sinks were identified from the DEM. These sinks were much shallower with a maximum depth of only 0.6 cm and a total volume of 0.08 m^3. Based on these findings, non-levelled blocks may display a variable number of sinks with variable volumes and depths. Ideally, it would be far more reliable to survey several blocks and derive an average volume over all the blocks surveyed. This approach, however, would be difficult due to the increasing number of blocks that are laser levelled. We can assume that unlike the cane blocks, which have been ploughed in the conventional way, blocks which are laser levelled would be almost devoid of sinks and display a uniform gradient across the entire length of the block.

Although there is a difference in the mean depth of sinks between the two cane blocks by a factor of around four, the results reveal that there is a strong similarity in their topographical features. It is evident from the DEM that these blocks have higher elevations in the middle of the block, but fall away towards the drains. Wilson (1995) showed a similar topographical trend for a surveyed cane block with elevations ranging from 0.70 metres AHD in the middle to 0.30 metres at the edge. This change in elevation is attributable to a land drainage technique called mole drainage, which is used by cane farmers to provide adequate drainage following flood events. It is apparent from these results that this strategy has successfully resulted in a fairly well drained surface for both blocks surveyed in this study. However, this practice may be undesirable where furrows run at right angles to the direction of the mole drains. Any surface water would be trapped by the furrows thus contributing to additional infiltration. Cane farmers in the Tweed have generally furrowed their cane blocks in this way and were not fully aware of the consequences of this type of ploughing had on surface water retention. Having been made aware of the impacts these farming practices had on the topography of their cane blocks, cane farmers now laser level their blocks and have changed the orientation of the furrows so that they run parallel to the direction of surface water runoff (Wilson, 1995). A gradient of 1 in 1000 to 1 in 3000 is now used to provide sufficient surface water runoff and reduce surface water retention (White *et al.,*1995; White, personal communication, 2001). Another farming practice which would have also contributed to surface water retention, involved the removal and dumping of drainage spoil between the drainage channels and the cane block during drain clearing and excavation (Wilson, 1995).

8.4.5.3 Estimation of Surface Water Infiltration Without Furrows

Rainfall infiltration, surface water retention and the generation of runoff from land surfaces is dependent on a number of factors such as topographic, soil and vegetation characteristics. It is beyond the scope of this work to present a detailed analysis of the phenomenon. However, here an order of magnitude estimate is provided.

Previous studies in the McLeods Creek Catchment have shown that the available water storage capacity of these shallow watertable, clay soils is of an order of 50 to 100 mm (Wilson, 1995; White *et al.,* 1993). The hydraulic conductivity of the oxidised jarositic layer is around 30 mm/hr and the unoxidised soil below that, at about 1 metre depth, has an hydraulic conductivity less than 1 mm/hr. According to White *et al.,* (1993), the low hydraulic conductivity of the unoxidised layer results in any further downward movement of water to flow horizontally into the drainage network. Given the high permeability of the jarosite layer, we would expect the watertable to rise rapidly in response to a rainfall event. This means that rainfall events that exceed 50 mm or have rainfall intensities much greater than 30 mm/hr, will generate surface runoff.

We can estimate the additional impact of the surface retention found for cane blocks 1 and 2 in Tables 8.5 and 8.6 for a 50 mm rainfall event. The estimated maximum infiltration volume resulting from a single rainfall event can be determined from the amount of rainfall and the surface area of the ploughed cane block. For cane blocks 1 and 2, the estimated recharge from a typical rainfall event of 50 mm would result in an infiltration volume of around 750 m^3 for cane block 1 and 300 m^3 for cane block 2. This is of course assuming that all the rainfall had infiltrated the soil and that there is no surface water runoff. The maximum sink volume found for block 1 was 0.9 m^3 and 0.08m^3 for block 2. So, in the original ploughed state, before furrow formation, these sinks represent an insignificant additional surface water storage capacity.

8.4.5.4 Impacts of Furrows on Surface Water Retention and Infiltration

Furrowed cane blocks can cause an additional infiltration of surface water and ponding if the cane furrows are ploughed at right angles to the direction of the mole drains. Since the furrows in these blocks run at right angles to the direction of flow we would expect additional surface water ponding to occur. The extra contribution in surface water infiltration from a non-laser levelled furrowed block has been estimated to be as high as 30% (White, personal communication, 2000). The dimensions of the furrows are fairly standard, usually measuring around two metres in width and 0.2 metres in depth. This width is just wide enough to allow modern harvesting equipment to fit between the rows of cane. The cane is planted on the crest or hill mound of the furrow to prevent the young cane plants from becoming waterlogged (Figure 8.35).

To determine the degree of surface water retention created by cane furrows, a second DEM was constructed which represented a series of furrows approximately 2 metres apart and 0.2 metres in depth. This second DEM had a grid size of 0.25 metres with five standard elevations for each grid cell ranging from 0.2 to 0 metres. The elevation series (0.2, 0.17, 0.1, 0.02, 0, 0.02, 0.1, 0.17) was repeated in the same sequence across the width of each cane block. These values were derived using a cosine function, which was determined from surface level. The new DEM was merged with the surveyed topographical DEM to produce a third DEM representing both topographical features and furrows. The cell size of the surveyed topographical DEM was re-sized to 0.25 metres prior to merging.

Figure 8.35 Young sugar cane plants are planted on the crest or hill mound of the furrow to prevent waterlogging.

The surface area and volume for each cane block was determined using the same methodology described in section 8.4.5.2 and involved using the "fill" command function in Arc/Info to produce a DEM with the furrows filled in. The final DEM shown in Figures 8.36 and 8.37 were derived from the subtraction of the filled DEM from the "unfilled" DEM. A TIN was created from the final DEM to determine the volume, surface and planimetric area of the furrowed depressions that would prevent surface water from entering the drainage system.

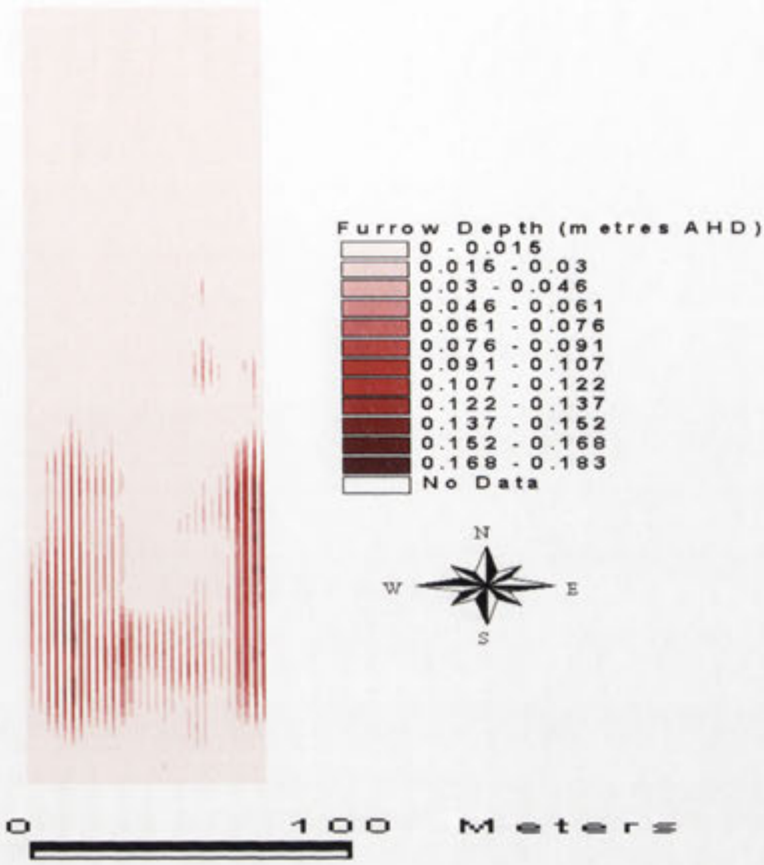


Figure 8.36 Furrow volume as depth of water retained by cane block 1.

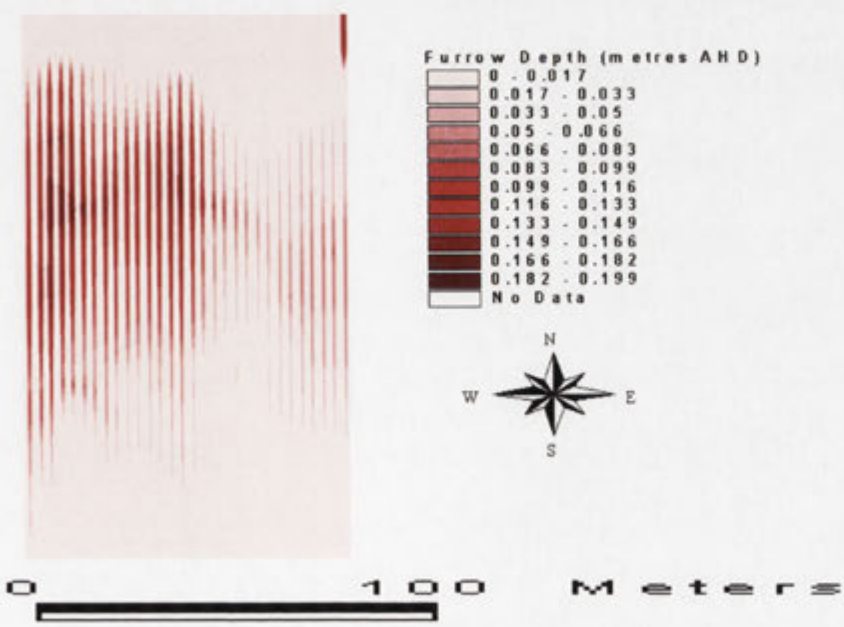


Figure 8.37 Furrow volume as depth of water retained by cane block 2.

Table 8.7 Furrow characteristics for cane block 1.

Furrow Characteristics	Result
Planimetric Area	**4393 m^2**
Surface Area	**4430 m^2**
Volume (determined from TIN)	**119.6 m^3**
Volume (determined from DEM)	**117 m^3**

The total volume of surface storage created by the furrows for block 1 is around 120 m^3 (Table 8.7). For a 50 mm rainfall event this represents 16 % of the total infiltrated volume.

Table 8.8 Furrow characteristics for cane block 2.

Furrow Characteristics	Result
Planimetric Area	**3579 m^2**
Surface Area	**3610 m^2**
Volume (determined from TIN)	**110 m^3**
Volume (determined from DEM)	**109 m^3**

From Table 8.8 the total volume of water held by the furrows for block 2 is around 110 m^3. This represents around 36 % of the infiltration in a 50mm rainfall event. A visual inspection of the DEM shows considerable areas where a combination of low relief and furrow configuration has the potential to trap surface water. Cane had always struggled to grow and often died in these areas during wet periods (R.Quirk, Personal communication, 2001). This indicates that surface water retention was a significant problem in these blocks prior to laser levelling.

This section has demonstrated how simple changes in land management practices in the sugar cane industry have not only led to better control of surface water retention and runoff, but have also provided more sustainable conditions for sugar cane production. Simple measures, such as changes to furrowing and laser levelling of cane fields, can reduce retention and thus residence times of surface water. The principle advantage of laser levelling and furrow re-orientation is to remove surface water mainly during flood events. Because of the high hydraulic conductivities of the surface soils, considerable infiltration can still take place on these levelled soils following periods of heavy rainfall, resulting in a rise in the watertable and the translocation of acid to the surface waters (Wilson, 1995).

8.4.6 Impacts of Forestation on Reducing Surface Flows

8.4.6.1 Introduction

Changes in land vegetation can have a major impact on the water balance of the catchment affecting both water yield and groundwater recharge. The impacts resulting from these types of land changes are clearly evident in regions such as the Murray Darling basin. Commonwealth and State governments have developed policies such as the "Forest Plantations 2020 Vision" (DPIE, 1997) as the panacea for dryland salinity. The projected increase in tree planting to over 3 million will change catchment hydrology and is planned to reduce salinity problems. According to Zhang *et al.* (2001), the trade-offs between the effectiveness of tree plantations and economic and environmental sustainability will depend on the spatial distribution of plantings. In order to determine these trade-offs, it is important to be able to predict catchment water balance relationships at several scales including the regional scale (Zhang *et al.*, 2001).

As discussed in section 7.4, Chapter 7, the watertable depth and the water balance of a catchment are principally controlled by rainfall and evapotranspiration. Previous research has shown that changes in vegetation cover, can dramatically alter the water balance of a catchment (Bosch & Hewlett, 1982). The impacts of vegetation and forest cover on catchment water balance are well documented (Hilbert, 1967; Bosch & Hewlett, 1982; Turner, 1991a) with work in this field going back to the early 1900s (Horton, 1919). This research has shown that changes in forest cover affects the water balance of a catchment through an increase or decrease in evapotranspiration. Deep rooted plants, such as trees, have access to greater soil-water stores than shallow rooted plants, such as grasses, which tend to reduce transpiration by closing their stomata when moisture in the upper soil profile becomes limited.

Some have taken this research further by also examining the impact of climate (Zhang *et al.*,2001) as well as vegetation type (Turner, 1991a) on evapotranspiration. Here, we examine a new method, based on Zhang *et al.*(2001) work, for predicting the hydrological impact of re-afforestation on the Cudgen Catchment.

8.4.6.2 Estimation of Actual Evapotranspiration

Methods used for estimating evapotranspiration at a local scale can be highly problematic due to the microclimatic variations and differences in vegetation cover and type (Allen *et al.*, 1998). Previous work by Holmes and Sinclair (1986) showed that out of a total of 103 catchments throughout Victoria, there was a difference in evapotranspiration rates between forested and grassland catchments. Similar results have been obtained from a study of 68 catchments in California in the United States (Turner, 1991a).

A simple model for determining evapotranspiration from catchments with varying proportions of forest and agricultural land use has been proposed by Zhang *et al.*(2001). The model, based on Eagleson (1982), assumes that the summation of annual transpiration from herbaceous plants (as well as soil evaporation) and forests is given as:

$$AET = f\ ET_f + (1 - f)\ ET_h \qquad 8.7$$

where AET is the total actual annual evaporation in millimetres, f represents the area fraction of the catchment containing forest, ET_f is the annual evapotranspiration from the forest and ET_h is the annual evapotranspiration from herbaceous vegetation, such as grassland. Determination of ET_f and ET_g requires an estimate of the potential evaporation (E_o) and the plant-available water coefficient (w*) for a given catchment. The estimate of AET for forested and grassed regions is derived from long-term annual mean rainfall ($\overline{P}$) (Zhang *et al.*, 2001) (Figure 8.38). The parameters for (w*) and for forested (E_{of}) and grassland catchments (E_{og}) were determined using data from Zhang *et al.*(1999). Equation 8.7 can be written as:

$$AET = \overline{P}\left(f\frac{1 + w^* E_{0f} / \overline{P}}{1 + w^* E_{0f} / \overline{P} + \overline{P}/E_{0f}} + (1-f)\frac{1 + w^* E_{0g} / \overline{P}}{1 + w^* E_{0g} / \overline{P} + \overline{P}/E_{0g}} \right) \quad 8.8$$

Where E_{of} is a constant equal to 1410 mm for forest cover and E_{og} is 1100 mm for grassland irrespective of location. The parameter w* is equal to 0.5 for grassland and 1 for forest.

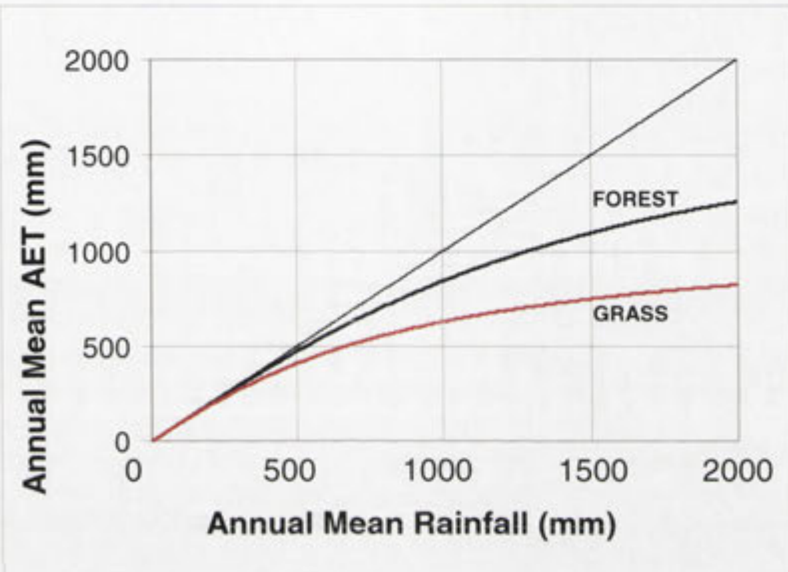


Figure 8.38 Relationship between annual mean actual evapotranspiration for all grass and all forest cover [Croke, (2002), modified from Zhang et al.(2001)]. A straight line is obtained when AET = $\overline{P}$.

8.4.6.3 Determination of Runoff Coefficient from Actual Evapotranspiration

The annual mean streamflow $\overline{Q}$ and annual mean runoff coefficient can be determined from the mean AET calculated using equation 8.8 together with the annual mean precipitation. This is based on the assumption that subsurface inflow/outflows and the water storage within the catchment do not change significantly over a year (Croke, 2002). Croke (2002) calculated streamflow and runoff coefficient for a range of forest covers using:

$$\overline{Q} = \overline{P} - AET \quad 8.9$$

An estimate of the runoff coefficient R_c is then:

$$R_c = \left(1 - f\,\frac{1 + w_f * E_{0,f}/\overline{P}}{1 + w_f * E_{0,f}/\overline{P} + \overline{P}/E_{0,f}} + (1 - f)\frac{1 + w_g * E_{0,g}/\overline{P}}{1 + w_g * E_{0,g}/\overline{P} + \overline{P}/E_{0,g}}\right) \quad 8.10$$

Croke (2002) showed that for a range of different climatic conditions, a correction factor could be applied to R_c, to derive the actual runoff coefficient, *RC*. The correction factor was determined from rainfall-runoff modelling derived from over 40 streamflow and rainfall gauging stations from northern NSW to southern NSW. This range traversed climatic zones from humid to dry conditions. An analysis of the observed runoff coefficient versus the predicted runoff coefficient ($RC/R_{c\,(predicted)}$) plotted against *PE* for these catchments produced a scatter plot shown in Figure 8.39. The correction factor was derived by fitting an exponential function to this scatter.

The application of this correction model to the runoff coefficient is unsuitable for those regions that have potential evaporation, outside the range shown in figure 8.39 (especially if *PE* is less than 1 m/yr). Values outside this range would require further testing. The annual potential evaporation for the Cudgen Catchment of 1.2 m/yr was previously estimated from pan evaporation data in section 5.3.6.2 (Chapter 5) and therefore lies within the range shown in Figure 8.39.

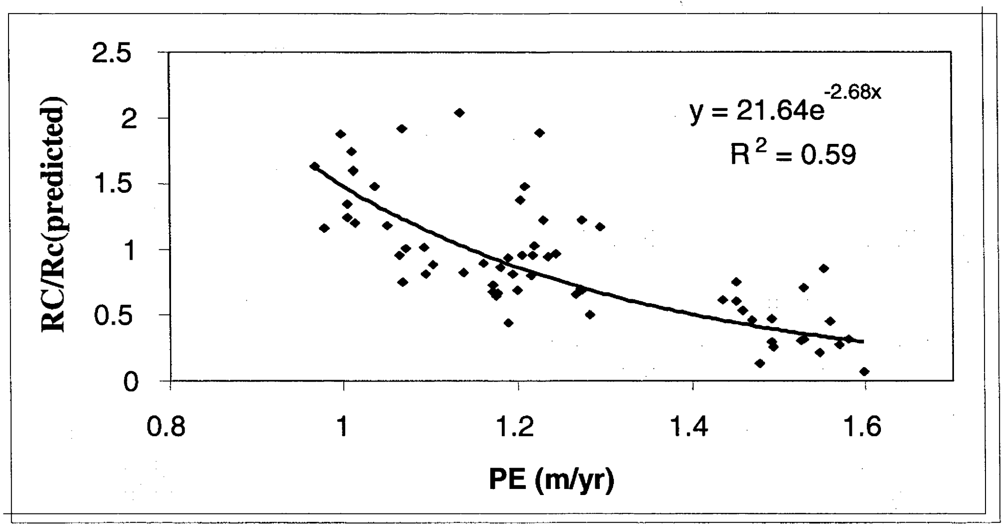


Figure 8.39 Exponential relationship between ratio of observed to predicted runoff coefficient and evapotranspiration which apply to a range of climate variables (Croke, 2002).

By using the expotential function derived from figure 8.39 the actual runoff coefficient *RC* then becomes:

$$RC = R_{c(predicted)}.f(PE) = R_{c(predicted)}.21.64\exp(-2.68 \times PE) \qquad 8.11$$

8.4.6.4 Determination of Forest Cover from Land Use Attribute Mapping

In order to assess the water balance-vegetation relationships at the catchment scale it is essential to have detailed knowledge of current land use activities. The land-use attributes for the Cudgen Catchment was previously discussed in detail in section 5.3.2 (Chapter 5). The relative area for each land use characteristic was derived from 1:25 000 attribute mapping (Hamilton, 1998) and is summarized in Table 8.9. An evapotranspiration *Et* rating of 1, 0.5 or 0 was then assigned to each land use attribute. A value of (1) represents high evapotranspiration (i.e., forest and water bodies) and a value of (0) represents no evapotranspiration (i.e., urban areas). Cropping, grassland and horticulture was assigned an *Et* rating of 0.5.

Table 8.9 Current land use activities for the Cudgen Catchment.

Land Use	Hectares	% of Catchment	Et Rating
Cropping	**677**	**8**	**0.5**
Horticulture	**1120**	**13**	**0.5**
Grassland	**2952**	**35**	**0.5**
Forest	**3209**	**38**	**1**
Water	**366**	**4**	**1**
Mining	**158**	**2**	**0**
Urban	**21**	**<1**	**0**
Utility	**26**	**<1**	**0**

The land-use activities such as horticulture, mining, urban, utility and grassland are classed as having lower evapotranspiration and are therefore assigned a value of 0.5. However, some horticulture plantations including orchards, banana, mangoes and macadamias would have high evapotranspiration and could be assigned an *Et* value of 1. These plantations cover a total area of 734 hectares or around 9% of the total catchment (Table 8.10). This area was included as part of the forest fraction. Furthermore, sugar cane cropping also has high evapotranspiration (Yang *et al.*, 1999) and for the purpose of this exercise was included as part of the forest fraction. As previously discussed in section 5.3.2, Chapter 5, recent field observations have confirmed that sugar cane cropping as a farming activity has diminished substantially with a majority of this area now taken over with pasture. Sugar cane farming is confined to the southern section of the floodplain and occupies an area of around 170 hectares or around 2% of the catchment (M. Tunks, Tweed Shire Council, personal communication, 2001). The remaining cropping area (507 hectares) was not included as part of the forest fraction.

Table 8.10 Current Horticultural land-use activities in the Cudgen Catchment.

Land Use (Horticulture)	Hectares	% of Total Catchment	Et Rating
Orchards	**493**	**6**	**1**
Banana	**201**	**2**	**1**
Mangoes	**32**	**<1**	**1**
Macadamia	**8**	**<1**	**1**
Other (vegetable/flower)	**386**	**5**	**0.5**
Total	**1120**	**13**	

By using the land use attribute data provided in Tables 8.9 and 8.10, the forest fraction cover for the Cudgen was estimated to be 52 percent of the total catchment. Although this represents a large area of the total catchment there is clearly an opportunity to invest in tree plantations, as a means of increasing evapotranspiration and decreasing water yield to the catchment.

8.4.6.5 Comparison Between Predicted and Actual Runoff Coefficients

The methodology outlined in the previous discussion, uses land use cover in conjunction with potential evaporation and rainfall to determine the runoff coefficient under different forest cover. This method is applicable as long as the potential evaporation, annual mean rainfall and the fraction forest cover are known and do not change significantly over time.

The annual potential evaporation for the Cudgen Catchment was estimated to be around 1200 mm when using a pan coefficient value of 0.8. Using equations 8.8, 8.9 and 8.10 this gave a predicted runoff coefficient of 0.39. The actual runoff coefficient, from streamflow and rainfall data for Uki and Eungella Sub-catchments in chapter 4, was close to 0.32. This represents a difference in the runoff coefficient of around 22%.. This difference is hardly surprising given the range of values of *RC/Rc(predicted)* for PE =1.2 m/yr in Figure 8.39. Here the results suggest that *RC/Rc(predicted)* = *1.2*, which is well within this scatter.

Therefore, based on these findings, we cannot be too confident about the absolute value obtained for the runoff coefficient under any conditions when using the approach of Croke (2002). However, in a relative sense, the model can provide an estimate of the degree of runoff reduction that can be obtained through changes to forest cover. The error values obtained here do not take into account the accuracy of the attribute mapping and small changes in the true forest fraction at any given time. Furthermore, estimates of the potential evaporation, previously determined from pan evaporation data and pan coefficient data (section 5.3.6.2, Chapter 5, p140-141), may be underestimated. Hoy (1977) found that the annual pan coefficients varied between 0.66 and 0.92, with coastal lakes or reservoirs having higher readings (ie ~0.9). By multiplying the annual pan evaporation for the Cudgen Catchment (~1500 mm) by a pan coefficient of 0.85 instead of 0.8 gives a potential annual evaporation of 1275mm which translates into a runoff coefficient of 0.32 when using equation 8.11. Methods used for estimating potential evaporation as well as evapotranspiration from pan evaporation are known to be highly problematic (Grayson *et al.,* 1996; Allen *et al.,* 1998). It is important to remember that discrepancies in the reflection of solar radiation, humidity, air circulation, heat transfer and retention, occur between crops and open water evaporation basins (Grayson *et al.*, 1996).

8.4.6.6 Predicted Impact of Forest Cover on the Annual Mean Runoff Coefficient

For the purpose of calculating the annual runoff coefficient under a range of forest cover regimes, an annual potential evaporation of 1275 mm and an annual mean rainfall of 1840 mm were used to examine the effectiveness of tree planting activities on reducing the annual mean runoff coefficient in the Cudgen Catchment. Here, we have used an annual potential evaporation of 1275 mm because it reflects the actual runoff coefficient of 0.32. The relationship between percentage forest cover and runoff coefficient for the Cudgen Catchment is shown in Figure 8.40. The results showed that there is a decrease in the runoff coefficient of around 0.01 for every 5% increase in forest cover.

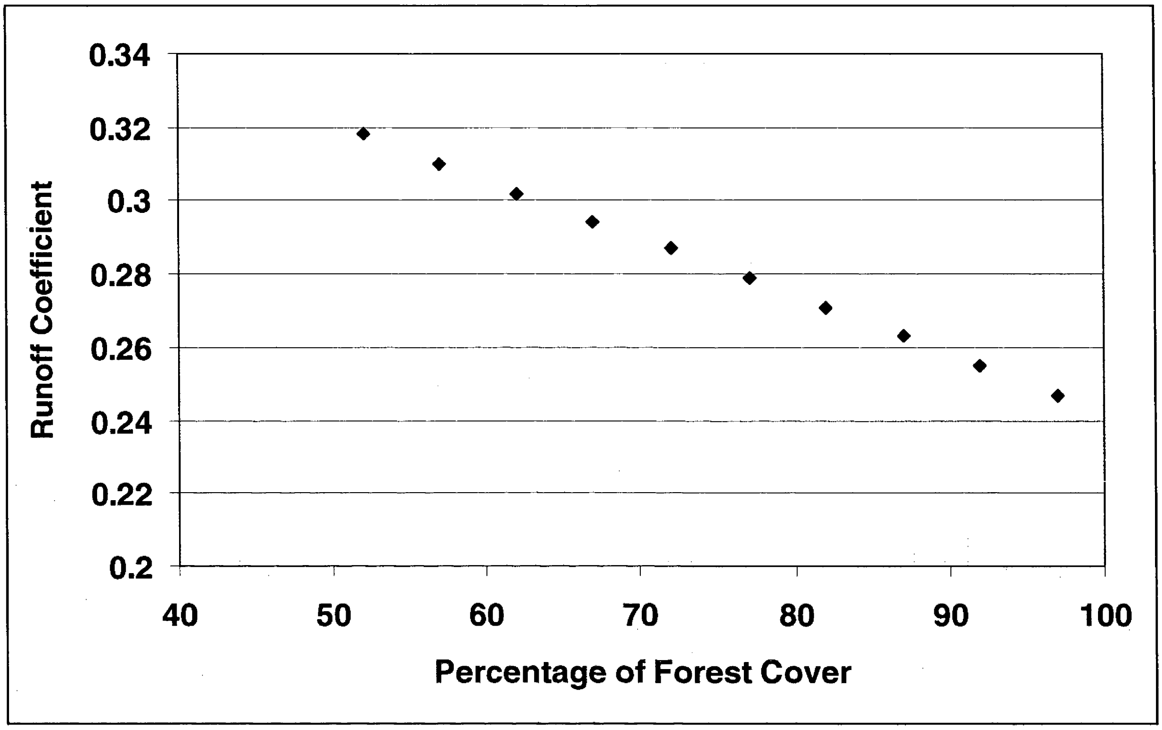


Figure 8.40 The relationship between percentage forest cover and runoff coefficient for the Cudgen Catchment when PE is 1275 and annual mean rainfall is 1840 mm.

Increasing the forest cover from the current 52 percent to 82 percent reduces the runoff coefficient from 0.32 to 0.27. This represents a decrease of around 15 percent in the runoff coefficient simply by increasing the forest cover in the catchment by 30 percent.

8.4.6.7 Predicted Impact of Forest Cover on Surface Flows

Surface water flows were also determined for each percentage forest cover by using the runoff coefficients derived from equation 8.11 (also shown in Figure 8.40) and the annual rainfall surface grid for the Cudgen Catchment developed in section 5.3.6.1, Chapter 5, p137. Annual runoff and flow accumulation grids were then generated using the methodology presented in Chapter 4. The flow accumulation grid was used to determine the accumulated flow at the entrance to Cudgen Lake. Table 8.11 summarises the accumulated annual flows for each percentage forest cover and an estimate of the percentage reduction in flow. By increasing the forest cover from 52 percent to 67%, results in a predicted 5% reduction in flow. This represents a 1,500 ML/yr reduction in surface water flow resulting from a 15 % increase in forest cover. Similarly, a 40% increase in forest cover could reduce the surface water flow by 19% or around 6,000 ML/yr. Realistically, it would not be feasible to have 92% of the catchment under forest cover. However, 82-87 % forest cover might be more achievable if forest plantations provide an alternative income for farmers. Surface water flow could be reduced from 30,000 ML /yr to 25,700 ML/yr if around 87% of the catchment was forested. This is a 4,300 ML/yr reduction in flow.

Table 8.11 Estimated impact of forestation on accumulated flows.

Percentage Forest Cover	Runoff Coefficient	Accumulated Flow (ML/yr)	Percentage Reduction in Flow
52 (Current)	0.318 (Current)	30,000 (Current)	0
57	0.310	29,700	1%
62	0.302	28,800	4%
67	0.294	28,500	5%
72	0.287	27,800	7%
77	0.279	27,000	10%
82	0.271	26,300	12%
87	0.263	25,700	14%
92	0.255	24,300	19%
97	0.247	23,800	21%

The results presented in section 8.4.2 showed that the diversion of upland flows could reduce the acidified surface water flow to Cudgen Lake from 30,000 ML/yr to 14,600 ML/yr (see Figure 8.16, p281). A forest cover of 87% would reduce this flow by an additional 4,300 ML/yr. These predictions estimate that a combination of tree planting and the diversion of upland flows could reduce the acidified streamflow through the lower floodplain by as much as 65%.

The surface water flows modelled and presented in Table 7.2 (Section 7.5, Chapter 7) showed that around 18,000 ML surface water flow altered the lake water pH dramatically from 6.7 under low flow conditions down to 4.3. However, the low monthly surface water flows of around 5,400 ML or less had little or no impact on lake water pH. A 62% reduction in surface water flow could effectively achieve a similar result reducing the overall flow from 18,000 ML/yr to around 6,000 ML/yr. Based on the water quality and rainfall results presented in Chapter 5, it is evident that the buffering capacity of the sea water is effective in neutralising lower acidic discharges.

Finally, the original attribute mapping indicates that around 677 hectares of the catchment supports sugar cane cropping. Because of the decline in this type of farming activity, sugar cane cropping was included as part of the original forest fraction used in this analysis. Sugar cane is deep rooted, has high evapotranspiration and is therefore an ideal crop for increasing the soil water storage capacity of the soil. If the 677 hectare area identified in the attribute was totally restored to sugar cane cropping, the percentage of forest fraction would increase from 52% to 60%. Using Table 8.11 as a guide this would represent around a 4 percent reduction in surface water flow.

8.4.6.8. Broader Implications of Forestation for the Cudgen

The idea of using either forest plantations or crops that have high evapotranspiration rates makes good sense from an economic and environmental perspective. The type of plantation would depend on its value as a commodity and how fast it will grow in this subtropical coastal environment. Eucalyptus plantations in coastal catchments could offer potential commercial opportunities as well as environmental benefits. In Brazil, eucalyptus trees represent around 57% of industrial plantations harvested for pulp and paper production (Swan, 1993). The use of eucalyptus as a timber source is becoming increasingly popular in some Asian and Latin American countries. eucalyptus trees are fairly fast growing, deep rooted and do not require fertile soils. They are also capable of growing on a range of soil types from acid to slightly alkaline soils pH 4.5-7.5. Many Australian native trees are well adapted to acid soils and poor drainage, including some species of Acacia and Eucalyptus (Signor, 2001).

Some of these species would be well-suited to coastal floodplains and could provide land owners with a profitable timber source. Table 8.12 lists some species of Eucalyptus and Acacia that would be most suitable for the Cudgen. The species listed in table 8.12 are specifically adaptable to coastal conditions and are able to withstand variable rainfall conditions. Some farmers in the Cudgen have already used eucalyptus plantations as an alternative to sugar cane production as part of a NSW and Commonwealth Government initiative (see Figures 8.41 and 8.42).

Figure 8.41 Hill planting of eucalyptus trees.

Figure 8.42 NSW and Commonwealth funded tree planting project in the Cudgen Catchment.

The benefits from tree plantations are also apparent in terms of reducing greenhouse gases. Previous discussions have referred to the association between an increase in global warming, climate change and high CO_2 levels in the atmosphere. Carbon dioxide levels have increased dramatically from 280 (ppm) to over 360 (ppm) by volume, following the Industrial Revolution (Velders, 1997) with levels expected to increase, unless attempts are made to reduce our reliance on fossil fuels. According to the terms of the 1997 Kyoto Protocol to the 1992 United Nations Framework Convention on Climate Change, some industrialised countries have made a pledge to reduce greenhouse gas emissions by 5% below the 1990 levels by 2008. To help these countries meet their obligation, the protocol allows for markets to be established in the trading of carbon credits. Industries and institutions can effectively offset emissions in carbon dioxide by buying the carbon sequestered through the production of biomass usually from timber plantations. The calculation of carbon credits for the Cudgen Catchment is discussed in more detail in the next Chapter.

Despite the terms and conditions of the Kyoto Protocol, there are countries that have refused to ratify the agreement and there are also problems relating to certain definitions used in the agreement such as afforestation, deforestation, and reforestation (see van der Maesen, 2000). Unfortunately, some industrialised countries such as Australia and the US might be excluded from any market in carbon trading if they do not ratify the agreement (J. Lindesay, personal communication, 2002).

The real challenge for land managers is the ability to develop forests that are sustainable and economically viable in the long-term. Effective plantation management is a key element for long-term sustainability. However, many of the current land owners in the Cudgen probably do not have the expertise, knowledge, or even the desire to undertake such an endeavour. Perhaps one way to encourage this type of activity is through government subsidies. The Bendigo City Council for example, provides a rate rebate for farmers to re-vegetate areas that have high groundwater re-charge rates (Mobbs, 1996). Although the Commonwealth Government provides subsidies for plantations in areas that have previously been cleared, there are currently no incentives for land holders to plant trees in degraded areas (van der Maesen, 2000). Clearly, a shift in Commonwealth government policy is required to assist in the implementation of this strategy.

For plantations to be effective in regulating catchment flows, harvesting and planting would need to occur on a rotational basis to ensure that the forest area fraction remains fairly constant. Although forest plantations would be confined to specific areas of the catchment, it should also be mentioned that they are but part of the larger landscape. This raises important issues relating to the impacts these plantations might pose to native flora and fauna species through the introduction of new species or from the harvesting of mature plantations. The development of a plantation management tool that combines GIS with catchment management tools and monitoring programs will help examine and track changes in the interaction between plantations and the natural environment.

Table 8.12 Coastal trees commonly used for timber production (Source: Modified from Signor, 2001)

Species	Common Name	Min Rainfall (mm/ yr)	Tolerant of	Prefers	Avoid	Comments
Acacia mearnsii	Black Wattle	600	Range of soils, poor drainage and exposed sites	Sandy, acid soils, especially shales and slates		Excellent timber for cabinet making and panelling
Acacia melanoxylan	Black Wood	700	Moderate drought	Deep acid clay loam >750mm	Heavy clays	Suitable for saw logs
Casuarina cunninghamiana	River Oak	500	Moderate drought	Slightly acid soils, river banks		Cabinet timber and panelling
Eucalyptus maculata	Spotted Gum	650	Range of soil types	Poor soils including acid soils		Very fast, growing excellent timber for cabinet making and panelling
Eucalyptus botryoides	Bangalay	700	Wide range of soils, poor drainage, moderate drought	Acid to neutral pH		
Eucalyptus pilularis	Coastal Blackbutt	750	Range of soils	Good drainage	Poor drainage alkaline soils	Versatile in growth and timber qualities
Grevillea robusta	Silky Oak	750	Range of soils including low pH (acid subsoils)			Allelopathic when grown in numbers

8.5 Discussion and Summary

Several land management options for reducing the impact of acidification on Cudgen Lake have been examined in this chapter. The options presented are specifically aimed at managing acid discharge from a large existing acidity store in the Cudgen floodplain. Remediation strategies may differ from catchment to catchment and therefore it is essential that the conditions and type of strategy for each catchment should be examined on a case-by-case basis. An examination of the hydrological and climatic conditions as well as the socio-economic issues, form an integral part of the decision making process. For the Cudgen Catchment, the concept of maintaining a high watertable as a management option was not considered, even though this type of management strategy is already being used to control acid discharge in some NSW coastal catchments (Bolton *et al.,* 2002). The practice of re-flooding sulfidic lowlands might be feasible in some regions of the world (Yin and Chin, 1982) it is simply not practical for the eastern coastal regions of Australia including the Tweed and Cudgen Catchments due to extreme climatic variability and existing land use rights (White *et al.*, 1997). It is also important to recognise that with a large existing store of acidity already in the soil profile, sulfuric acid will continue to leach out for many years after re-flooding.

The land management strategies examined in this chapter showed that in order to reduce sulfuric acid surface water loads, a combination of two or more strategies are required. Out of all modelling scenarios that were examined for their impact on water loads, the most effective of these included a combination of minimum drainage and widespread capping (Table 8.13). The combination of these two strategies reduced acid loads by around 32%. Although capping of acid sulfate soils can be an effective remediation strategy according to the modelling results obtained here, it is also expensive and probably beyond the affordability of many catchment management groups. Some of the cost issues associated with capping as a form of remediation are analysed and discussed in more detail in Chapter 9.

The optimum thickness of the capping material was determined form previous investigations into the relationship watertable depth and the consolidation of swelling soils. The optimum capping thickness was approximately 0.8 metres. Clearly, capping of all acid sulfate soils in the catchment is simply not practical or economical and therefore priority should be given to areas that are most degraded such as scalded sites. Thus, accurate soil survey techniques are crucial in the determination of priority areas. Fortunately, for the Cudgen Catchment the construction of the Yelgun to Chinderah roadway has effectively capped 225 hectares or 28% of the ASS high risk area resulting in a predicted reduction in acid water loads of 29% under minimum drainage conditions and 25% under current drainage capacity. While, these types engineering projects often create divisions and conflicts between developers and community groups, they can also provide water quality benefits in regions affected by acid sulfate soil drainage.

Table 8.13 Summary of Land Management Remediation Strategies for reducing acid surface water loads to Cudgen Lake. Values are expressed as a percentage reduction in acid water loads.

	Drainage Density			
	Minimum	**25%**	**50%**	**100%**
No Further Remediation	12%	1%	0%	0%
34% Capped	32%			23%
17% Capped	27%			16%
10% Capped	20%			9%
3%Capped	14%			3%
Diversion	27%			10%

Since agricultural drains reduce residence time of surface water and act as a conduit for the transportation of acid, a policy of drain reduction and re-design should be adopted. However, alterations to the drainage network and the re-design of drainage and levee systems should be examined in association with current and future land use activities and should only be carried out in conjunction with suitable land-forming techniques, such as laser levelling and changes in ploughing practices. These land-forming techniques allow for direct runoff of non-acidified surface water and help reduce surface water infiltration. Such techniques are commonly used by cane farmers in the Tweed Catchment and have allowed farmers to plant crops immediately after periods of heavy rainfall due to a reduction in soil saturation (R Quirk, personal communication, 2001).

The water quality results presented in previous chapters have shown that the mobilisation and transportation of acid is greatly influenced by surface water flow and watertable dynamics. It is important to recognise, however, that although it is possible to reduce sulfuric acid water loads through a combination of different remediation strategies, as discussed in this chapter, the modelling results indicate that acid loads are still elevated. Drastic drain reduction strategies are not an effective remediation option unless measures are also taken to address the problem of surface water retention. However, the results also showed that it is possible to reduce sulfuric acid surface water flows through the catchment by adopting flow diversion and tree planting strategies. A combination of tree planting and the diversion of upland flows could effectively reduce the acidified streamflow through the lower floodplain by as much as 65%. A reduction in surface water flow allows for a more manageable approach to treating acid loads due to smaller flow volumes. The neutralising capacity sea water may, in some cases, prove to be sufficient in buffering small acidic volumes.

In summary, the management options for the Cudgen include:

1. Reconstruction of the current drainage network in association with improved land management techniques such as laser levelling;
2. Plant deep-rooted crops or trees with high evapotranspiration rates to ensure that runoff is minimised. A reduction in intensive sugar cane cropping over the years has probably resulted in an increase in surface water runoff. The establishment of eucalyptus forest plantations will lower watertable levels while at the same time provide land owners with a viable income from timber products and carbon credits;
3. Re-routing of upland flows and the installation of levee banks around acid sulfate soil regions;
4. The installation of passive and active lime dosing systems to neutralise acidity from low surface water flows;

5. Capping of acid sulfate soil regions, especially in regions where there is severe acid scalding and;
6. An improved water quality data management and collection system for improved on-ground management of acid discharge events.

CHAPTER 9
Cost of Remediation and Ecosystem Services for the Cudgen Catchment

Chapter 9. Cost of Remediation and Ecosystem Services for the Cudgen Catchment

9.1 Introduction

In theory, acid discharges can be treated by a range of techniques, however the costs associated with some treatment options are so high that they are simply not economically feasible. Some agricultural enterprises, such as broad-acre agriculture, (ASSMAC, 1999a) cannot afford to reinvest profits into remediation work. In some cases, remediation costs have been as high as $AUD100,000 per hectare (ASSMAC, 1999a). According to White (2001a), applying these techniques to treat the entire coastal floodplains of eastern Australia, could well exceed hundreds of millions of dollars. The cost associated with remediation projects is an important consideration in the decision making process and is usually the deciding factor that affect the types of remediation works to be implemented. This chapter provides a brief overview of the costs associated with some of the remediation strategies discussed in the previous chapter with particular emphasis on the true cost of ecosystem services and their benefits to the wider community.

9.2 Measuring the Costs of Environmental Management

The costs resulting from the impacts of acid sulfate soils can be measured in terms of environmental or ecological (i.e., loss of biodiversity), economic (ie loss in productivity) and social (i.e., loss of community amenities and values) costs (See Figure 9.1). Although not widely acknowledged, these factors are inextricably connected. Decision making often works on the ideology that ecological sustainability is possible if the economy is sound (Figure 9.2a). A more modern and realistic approach is to view the economy as being encapsulated by society and that both the economy and society are both dependent on ecology and resources (Figure 9.2b)(Lowe, 1994; Daly, 1992). This is the case in the coastal zone, particularly where there is a strong dependence on the sustainability of environmental resources for continued economic growth, especially with respect to recreation and tourism. Unfortunately, conventional or "neoclassical" economics fails to recognise the true value of a resource and the costs associated with its use (Faber *et al.*, 1996). There is a perception that conventional economic systems operate outside the realm of ecosystems and that sustained economic growth can be achieved through technological development at the expense of environmental degradation (Asafu-Adjaye, 2000).

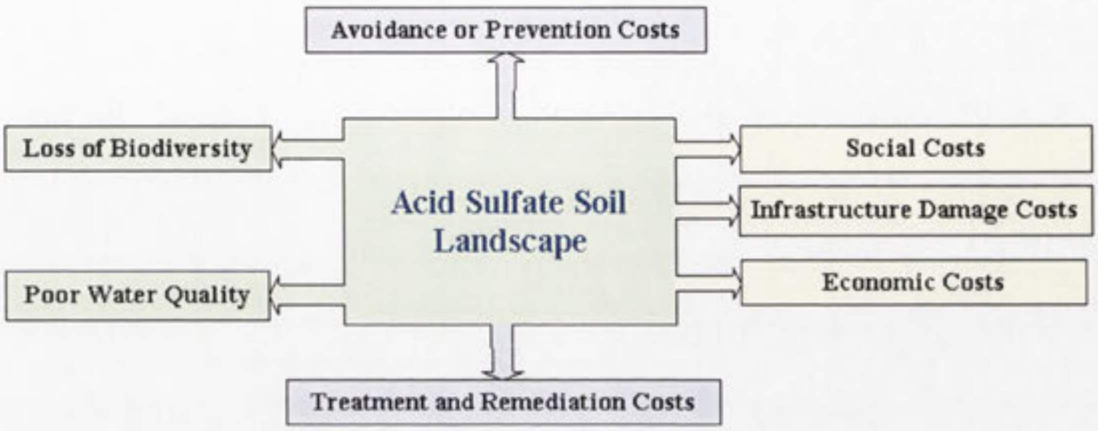


Figure 9.1 An overview of the related environmental, social and economic costs of Acid Sulfate Soils.

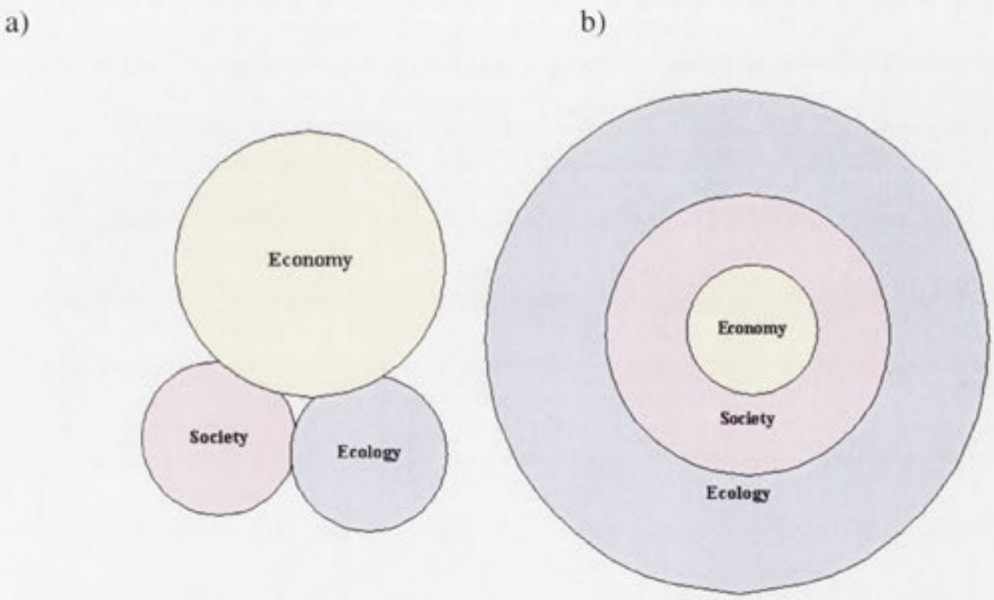


Figure 9.2 The framework of ecologic, economic and societal sustainability. a) The conventional model which assumes that environmental sustainability is possible if the economy is strong and; b) the model for the future, in which the economy and society are both dependent on the world ecology and its resources [Source: State of the Environment, Australia (1996), adapted from Lowe, (1994)].

Because the environment plays a significant role in economic performance and in maintaining a high standard of human welfare, there is an ever increasing need to combine environmental, social and economic information into one accounting system, thus creating a framework for the management of coastal ecosystems (UNSO, 1990; Lowenstein, 2001). Although there is no integrated accounting system that can accurately calculate the economic value of an environmental resource, several authors have attempted to define its true value in dollar terms.

Turner (1991b) and Barbier (1994) believe that estuaries and wetlands offer a greater value to the community when left undrained and in their natural condition. Whereas, Costanza *et al.* (1998) regard terrestrial and marine systems such as estuaries, river systems, swamps, coral reefs and floodplains as productive ecosystem services that have a true monetary value based on the value of their Net Primary Production (NPP), measured in grams per square metre per year (Figure 9.3). Natural swamps/floodplains, for example, have a monetary value of $US19,600 per hectare per year while estuaries are valued at $US22,800.

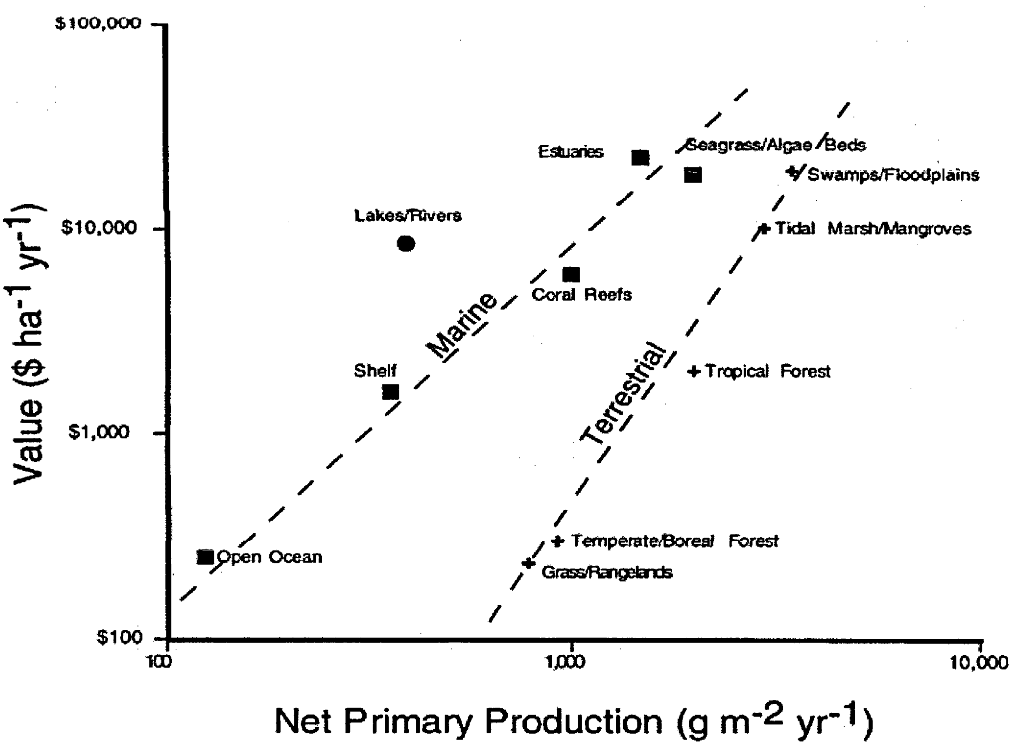


Figure 9.3 NPP versus the value of a number of marine and terrestrial ecosystem services (Values are expressed in US Dollars) [Source: Costanza et al., (1998), p71].

By applying these costs to the Cudgen, we can estimate the total value of ecosystem services for the entire catchment assuming that the NPP values described by Costanza *et* *al.* (1998), are fairly standard regardless of geographical location. Table 9.1 provides a breakdown of the marine and terrestrial ecosystem services for the Cudgen and their value derived from the NPP. The total value from ecosystem services for the Cudgen Catchment is around $US11 million per year or $20 million Australian dollars per year*.

Calculating the true value of an economic resource using this type of methodology has become a topic of much debate. According to Ayres (1998), the total global ecosystem service ($US33 trillion) far exceeds the accumulated Gross World Product (GWP) estimated at $US18 trillion and that this undermines basic economic theory. The reasoning or argument behind this theory is that the eco-sector would need to pay $US33 trillion to other sectors of the economy in order to protect the environment and that, therefore, the GWP would need to be at least twice this amount or $US66 trillion for this to occur. However, it should also be remembered that the GWP is simply a measure of those goods and services that are marketable, whereas ecosystems are not an integral part of the market place, but nevertheless do in fact produce "real income" in the form of a "contribution to human welfare" (Costanza *et al.*, 1998).

Table 9.1 Total value of ecosystem services for the Cudgen Catchment based on Costanza et al. (1998).

	***Area (ha)**	**Value ($US/ha/yr)**	**Total Value ($US/ha/yr)**
Lake & Streams	366	$8,500	$3,110,00
Forrest	3,209	$300	$969,000
Grassland	2,952	$230	$953,000
Backswamp	311#	$19,600	$6,089,00
Total Value			$11,122,00

**Based on attribute mapping (Section 5.3.2, Chapter 5, Hamilton, 1998).*
 # Estimate based on WBM Oceanics Australia,(1998).

The conservation of an ecosystem resource to maximise human welfare is fundamental to ecologically sustainable development. Ecologically sustainable development is a complex balance between economic development and ecological sustainability that protects natural ecosystems and the welfare of humans and other species for generations to come (Commonwealth of Australia, 1996). It should recognise the "intrinsic" (inherent) and

**Based on an exchange rate of 0.55. Values will vary depending on the exchange rate.*

non-intrinsic (i.e,. the market value) net benefits and costs of resource management and use as depicted in a diagrammatical representation by Aaso, 2000 (See Figure 9.4).

Asafu-Adjaye (2000) and others (Turner *et al.,* 1994; Tisdell, 1993) have argued that the net benefit of a resource may in fact decline with continued use, resulting in a net loss in human welfare (red dotted line, see Figure 9.4). The conservation of the natural environment is therefore essential in order to increase or sustain economic productivity (Tisdell, 1993). The curved black line in Figure 9.4 represents the net benefits derived from resource management whereas the blue line is the net cost derived from resource utilisation, including its management. The optimum net benefit to society is therefore represented as O and therefore the optimum cost of resource use and management is given as C. In the context of catchment management for the Cudgen, sustainable development takes place when a balance can be found between the net benefits of the lake (i.e., fishing and recreational activities) and land used for urban development or farming, compared to all the net costs derived from their use.

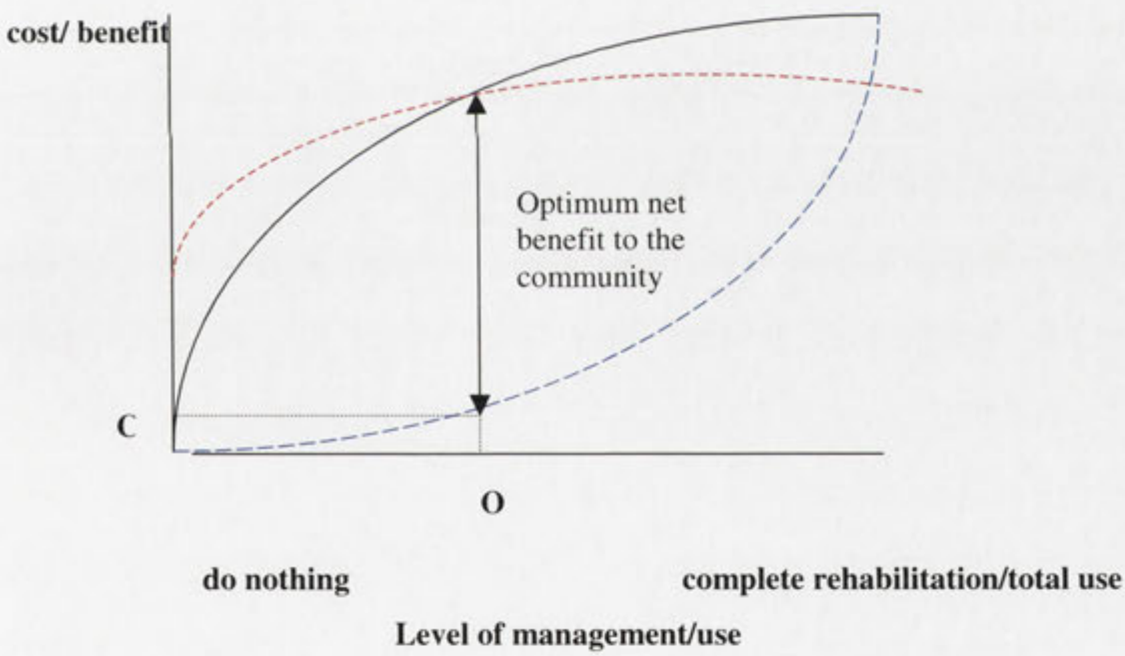


Figure 9.4 The costs and benefits of resource management and use. [Source: Aaso, (2000) p 7, previously adapted from Asafu-Adjaye, (2000)]. Blue line is the net benefits derived from resource use including its management. The red line is the net benefit of a resource. The black line is the net benefit derived from resource management.

For the Cudgen, continued resource use has resulted in a decrease in the net benefit of resource use almost to the point where it has a no value. Although the net benefits of resource use may decrease with increasing use, the net benefit of resource management to the community still remains high suggesting that there is some intrinsic value to the community through continued resource management long after the resource is considered to have no real value.

Environmental systems are multifunctional, having a range of values including direct and indirect utilitarian values as well as scientific and educational values (Dovers, 1996) (see Table 9.2). They also have potential utilitarian values described in economic terms as "option value", which is the willingness of the present generation to invest in the conservation of a particular resource for future generations (Turner *et al.*, 1994). Pearce (1993) regards the Total Economic Value (*TEV*) of environmental systems as:

$$TEV = O_v + D_v + I_v + E_v \qquad 9.1$$

Where O_v is the "option value", D_v is the "direct use value", I_v is the "indirect use value" and E_v is the "existence value".

Table 9.2 Examples of different environmental system values.

Direct Use Value	Indirect Use Value	Option Value	Bequest Value	Existence Value
Recreation	***Ecosystem Services***	***Future use either direct or indirect***	***Use and non use values for intergenerational legacy***	***Biodiversity***
Agriculture	***Climate stabilisation***	***Future Information***		***Cultural, Heritage values***
Education	***Carbon sequestering***			***Community values***
Grazing	***Catchment protection***			***Aesthetic***

[Source: Bagri et al., (1998)]

The economic value of environmental conservation is often seen as a "trade off" between the benefits of land use versus the benefits of conservation. According to Turner *et al.*, (1994) the economic justification for conservation can be defined as:

$$[Bc - Cc] > [Bd - Cd] \qquad 9.2$$

in which *Bc* is defined as the benefit derived from conservation and *Bd* represents the benefit derived from development or resource use. The parameters *Cc and Cd* represent the cost of conservation and development, respectively. The "opportunity cost" of conservation is therefore [*Bd* – *Cd*]. In order for conservation to take place there is a requirement for some trade-offs or sacrifices to be made. Unfortunately, the conservation of ecological resources is at a disadvantage. Development activities, including agricultural farming, often receive government subsidies in the form of tax concessions or tax breaks. Conservation activities are generally not subsidised to the same degree as alternative land uses (Turner *et al.*, 1994). Conservation activities conducted by Landcare groups for example, are carried out on a purely voluntary basis.

In order to ensure that environmental resources are protected from land use activities it is necessary to develop land management strategies that offer both long-term environmental sustainability and profitability to land holders. However, this may also mean that the profits originating from a particular enterprise are used to ensure that future environmental resources are adequately protected. Under the National Strategy for Ecological Sustainable Development (COAG, 1992) the Commonwealth Government is committed to supporting the sustainable use of land and water resources to ensure the long-term viability of Australian agriculture. Although the Commonwealth Government's commitment to the environment is small, representing around 0.2% of the total national budget allocation (Commonwealth of Australia, 1999) it has been shown that the benefits-to-cost ratio for funds spent on the environment is high (Driml, 1994).

Some industry sectors have invested considerable amounts of funding on sustainable land management practices, while others have been slower to act. The NSW sugar industry in consultation with the NSW Environment Protection Agency, have developed ASS best practice guidelines for: "*delivering environmentally and economically sustainable sugar cane production*".
(http://www.nswsugar.com.au/pages/Grower/Best%20Practice%20Guidelines.htm).

There is anecdotal evidence that these sustainable land management practices have increased farm gate production by up to 20% (ASSMAC, 1999a). Sugar cane farmers on average spend up to $AUD400 per hectare on laser levelling and around $AUD400 per hectare annually to lime paddocks (ASSMAC, 1999a). Clearly, certain industries have the capacity to finance ASS best management practices. Agricultural enterprises such as sugar cane and tea tree, which have gross margins of around $AUD850 and $AUD3000 per hectare respectively (Mullen and Kaur, 1999) can easily afford the implementation of improved land management strategies. The beef cattle industry on the other hand, has endured fluctuating commodity prices and economic hardship, which has resulted in low gross margins of between $AUD40 to $AUD90 per hectare (Mullen and Kaur, 1999). This is a worrying situation for a majority of catchment managers as cattle grazing industry occupy 80% of high ASS risk areas (ASSMAC, 1999a). To date, there are no best management practice ASS guidelines for the Beef and Dairy industries (Woodhead, 1999).

9.3 Land Remediation Costs Analysis

The four major strategies examined in this study require major land re-shaping and excavation. These include the infilling of drains, laser levelling, capping and diversion of upland flows. Such strategies could incur high costs depending on the amount of work that is carried out and the duration of the project. Apart from the costs associated with excavation and earth moving works, there are also costs incurred as a result of treating any discharge originating from remediation works, as well as the costs of laser levelling. This additional discharge would create only a short-term problem and could be treated using lime.

9.3.1 Cost of Capping

According to the Tweed Shire Council, most of the base filling material required for capping and the infilling of drains could be sourced on-site from a local quarry within the catchment or otherwise off-site from a clay quarry near Brisbane (M. Tunks personal communication, 2001). The cost of capping is based on a number of factors including the cost of the capped material, cost of lime treatment, truck hire for fill transportation, and the excavator hire for fill quarrying. If the material is to be sourced on-site, then it is necessary to estimate the cost of excavation and transportation to the treatment site. The cost of one excavator and grader is estimated at $AUD85.00 per hour. It is assumed that one excavator, three tippers and one grader can work 90 m^3 of soil per hour which is equivalent to 720 m^3 per day. If the clay material is to be sourced off-site, then it is necessary to purchase the clay from a commercial quarry some distance away from the treatment site. The Council estimated the cost of clay material using off-site sources at approximately $AUD10 m^3. EPA Victoria (2001) estimates the cost of clay for capping land-fill sites at around $AUD5 m^3. Broadscale liming operations would be carried out at 5 tonne/hectare at $AUD100 per tonne of lime.

It was estimated in section 8.4.3.2 (Chapter 8) that around 0.8 metres of capped material would be of sufficient depth to provide an effective cap against further acid discharge. This is equivalent to 8000 m^3 of clay material per hectare of land. Table 9.3 summarises the total costs associated with each of the three capping scenarios assuming that the capping material was sourced locally or on-site. Table 9.4 provides the total cost based on off-site sourcing of capped material.

Based on the cost analysis shown in Tables 9.3 and 9.4 there is approximately a three-fold difference in cost, depending on whether the capped material is sourced locally or off-site. Overall, the cost of capping is high. To cap 34% of the floodplain would incur a remediation cost between 6 and 22 million Australian dollars, depending on where the material is sourced. This, of course, does not include the cost of site preparation such as survey operations and laser levelling which is generally around $AUD100/ha and $AUD35/ha respectively.

Table 9.3 Total costs (in $AUD) associated with different capping scenarios assuming the material can be sourced locally or on-site.

Percentage of floodplain containing ASS capped	**Excavator Hire (Eh) 720 m^3 per day @ $680 per day**	**Grader Hire (Gh) 720m^3 per day @ $680 per day**	**Lime Treatment (Li) ($100/T) @ 5 T/Ha**	**Truck Hire (Th) 720 m^3 per day @$880 per day**	**Total Costs Ba+Eh+Gh +Li+Th**
3% (18 ha)	136,000	136,000	9000	176,000	457,000
10% (68 ha)	513,400	513,400	34,000	664,400	1,725,200
17% (129 ha)	974,666	974,666	64,500	1,261,040	3,212,000
34% (251 ha)	1,941,777	1,941,777	128,500	2,512,400	6,525,000

Table 9.4 Total costs (in $AUD) associated with different capping scenarios for *off-site sourcing of material.*

Percentage of floodplain containing ASS capped	**Cost of capping material* (Ba) ($10m^3)**	**Grader Hire (Gh) 720m^3 per day @ $680 per day**	**Lime Treatment (Li) ($100/T) @ 5 T/Ha**	**Total Costs Ba+Eh+Gh+ Li+Th**
3% (18 ha)	1,440,000	136,000	9000	1,585,000
10% (68 ha)	5,440,000	513,400	34,000	5,987,400
17% (129 ha)	10,320,000	974,440	64,500	11,358,940
34% (251 ha)	20,560,000	1,941,400	128,500	22,629,900

* *Includes transportation costs*

The construction of the Yelgun to Chinderah highway has effectively capped around 225 hectares of the lower Cudgen floodplain. These engineering works have reduced the cost of capping by as much as 88%. This is based on the initial cost of capping 34% of the floodplain. Construction work of this nature can provide huge savings, while at the same time serve as an effective long-term remediation strategy. Capping in the Cudgen catchment has recently commenced (M. Tunks, personal communication, September, 2004) as part of the Acid Sulfate "Hot Spots" priority areas for remediation project (ASSMAC, 1999b). Figures 9.5 and 9.6 show capping of ASS in the Tanglewood Estate, an ASS Hot Spot priority area. The identification of acid "hot spots" could mean that a much lower fraction of the floodplain could be capped. The identification of areas for remediation require accurate ground and soil surveys.

Figure 9.5 Capping material (compacted clay) is transported to the Tanglewood Estate, Cudgen floodplain by truck.

Figure 9.6 Capping of ASS in the Tanglewood Estate, Cudgen floodplain.

9.3.2 Cost of In-filling of Drains

The same material and costs per cubic metre of fill per day is also applicable to in-filling of drains, however, the amount of fill required is much less than the amount that would be needed for capping and is easily sourced on-site from spoil heaps (M.Tunks, personal communication, 2004). In the case where drains are greater than 6 metres in width, fill material may need to be sourced from the local quarry. This would incur a cost for the excavation and transport of material and has therefore been included in the final costing. Drains and fill material should be strategically limed prior to filling operations. The correct lime dosage rates prior to filling will depend on the dimensions of the drains. A summary of the costs associated with the filling of agricultural drains for different drainage scenarios is shown Table 9.5. A detailed spreadsheet of the costs and treatment for each drain is provided in Appendix E.

Table 9.5 Total costs ($AUD) of drain filling for different drainage scenarios.

	Treatment						
Drainage Density	$A	$B	$C	$D	$E	$F	Total
Minimum	2,701	10,983	1,407,535	53,045	318,912	68,646	1,861,822
25%	1,969	8,069	1,029,618	38,077	323,560	49,276	1,359,571
50%	1,174	4,932	692,319	7,879	138,651	10,197	855,155

Total drainage area to be filled: Minimum = 337,671 m^3, 25%= 246,240 m^3, 50%= 146,807m^3

$A= Lime Treatment of Water (Assuming the drain is holding 10% of its depth capacity)
$B=Lime Treatment of Drain Basin (Allowing for 2m buffer (1m either side of drain) at a lime application rate of 5T/Ha)
$C=Lime Treatment of Fill Material
$D=Excavator Hire (Eh) 720 m^3 per day @ $680 per day (applied to drains greater than 6 metres wic
$E= Grader Hire (Gh) 720$m^3$ per day @ $680 per day
$F=Truck Hire (Th) 720 m^3 per day @ $880 per day (applied to drains greater than 6 metres wide)

The total cost of filling individual drains varies from $AUD200 to $AUD58,000, depending on the level of treatment and the dimensions of each drain. The average cost is around $AUD5,000 per drain. Sugar cane farmers in the McLeods creek region pay around $AUD1500 per drain (R. Quirk personal communication, 2002), however, a majority of cane farmers generally own their own earth moving equipment which reduces the costs considerably. Clearly, lime treatment of fill material (Treatment $C) is the most expensive part of the treatment process. Finally, it is essential that surveying and laser levelling operations be carried in concert with drain filling operations in order to avoid low spots which would retain surface water.

9.3.3 Cost of Diversion Channel and Levee

The cost of constructing a diversion channel depends on the size of the channel and whether post-acid discharge treatment is required. Spoil from the diversion could be used for the construction of the levee bank. The average cost of construction is around \$AUD720 –\$AUD1000 per m^3 (M.Tunks, personal communication, 2004). To construct a diversion channel around the acid sulfate soil regions as shown in Figure 8.11 section 8.4.2, Chapter 8 would involve building a channel 8.7 km in length. Ideally, in order to cope with an average 6,500 ML of surface flow per year, the channel would also need to be 10 metres wide by 2 metres deep. Therefore the total amount of soil that would need to be removed is around 174,000 m^3. This gives an overall estimated cost of between \$AUD174,000 and \$AUD240,000.

9.4 Cost of Using Technology Systems for Treating Small Acid Outflow Events

The results presented in Chapter 8 indicate that acid discharge events will still take place despite the implementation of these remediation strategies. Although these results had shown that surface water flows can be substantially reduced through effective remediation strategies, the results also identified that acid surface water loads entering Cudgen Lake will still remain at high levels (270-400 tonnes/yr) regardless of the type of strategy used. The water quality results showed that the small tidal exchange that exists in Cudgen Lake has some effect on neutralising small acid slugs from low surface water flows. Using the natural tidal exchange to help neutralise these small discharge events may not always prove to be reliable and there may be cases where discharge events might be small but are above the threshold point in which sea water can effectively neutralise any surface water acid entering the lake. Under reduced flow conditions, through tree planting strategies and diversions of upland flows, the acid from these low surface flows are able to be managed more effectively through the use of appropriate technologies.

Systems such as active lime dosing, can effectively neutralise small acid discharge events which accompany low surface water flows. These systems are commercially available for treating small acid discharge events via reaction with alkaline reagents or amendments such as hydrated lime [Ca $(OH)_2$], quicklime (CaO) or limestone ($CaCO_3$) and have been used effectively in the management of acid mine drainage runoff (Taylor *et al.*, 1997). Other neutralising reagents readily available on the market include soda ash, magnesium hydroxide, red mud, caustic soda and caustic magnesia. The costs of these reagents vary significantly. Limestone is the cheapest at around $AUD25 to $AUD30 per tonne (Figure 9.7). Active dosing systems range in size from large high density sludge plants to small portable chemical dispensing systems, as well as in-stream dosing systems (Aquafix plants). The capital cost for a standard commercially produced active dosing plant is between $AUD130,000 and $AUD200,000, with maintenance costs estimated at around $AUD30,000 per annum (Taylor, personal communication, 2002). However, the on-going running cost of treatment can be expensive, depending on the reactivity and cost of the reagent. It is not uncommon for reagent efficiencies to be less than 50%, thus increasing treatment costs substantially (Murphy *et al.*, 1999). Therefore, for maximum cost effectiveness, careful consideration should be given to the type of dispensing mechanism and the choice of neutralising reagent. Hydrated lime is suitable for high environmental flows and highly acidic conditions (Murphy *et al.*, 1999), however, it is not uncommon for alkalinity levels in drain water to rise to unacceptable levels (I.White, personal communication, 1999).

Out of all the lime-based reagents, quicklime is perhaps the most effective neutralising reagent due to its high reactivity. Unfortunately, the use of quicklime as a neutralising reagent can be limited due to difficulties in handling and dispensing. There is also the problem of 'over-shooting' the neutralisation point when using quicklime. Limestone or calcium carbonate, on the other hand, is also an effective neutralising reagent- although it has a tendency to form an external coating because of its low solubility which can also inhibit its reactivity (Taylor *et al.*,1997). Unlike conventional dosing systems the more modern systems generally take this effect into account, by controlling the grain size of the limestone slurry through the use of sophisticated screening systems.

The cost difference between hydrated lime and calcium carbonate is significant. The cost of 300 tonnes of hydrated lime (Ca $(OH)_2$), is estimated at around $AUD150-$AUD250 per tonne which is approximately \$AUD45,000 per year. Whereas, 500 tonnes of limestone ($CaCO_3$), based on an 80 % efficiency level, at \$AUD25 per tonne, is approximately \$AUD12,500 per year. Potentially, over \$AUD30,000 could be saved each year, simply by using a cheaper reagent. These costs are based on treating the maximum acid load (~400 tonnes). The final cost of reagent could be lower depending on the type of remediation strategy used.

There are also several other chemical methods generally applicable to treating the products of acidification. These include the adsorption of heavy metals by coagulants and flocculants and the physical or chemical oxidation of drainage waters to aid the conversion of aqueous Fe (II) to insoluble ferric hydroxide (see Murphy *et al.,* 1999).

The use of passive chemical treatment or limestone reactive barrier systems has also been used by the mining industry as an alternative to active dosing systems for treating acid mine drainage for more than 20 years (Pearson and McDonnell, 1975; Cravotta and Trahan, 1999). Unlike active systems in which the reagent is manually fed into a tumbler, passive systems generally rely on drainage channels or structures filled with aggregate limestone to neutralise acid water. Often, large volumes of aggregate limestone are used to compensate for the effect of reduced reactivity through armouring reactions (Ziemkiewicz *et al.*, 1995). Both active and passive systems are currently being trialed in the McLeods Creek region for their effectiveness in reducing acidity levels in drainage water from cane farms (Desmier *et al.*, 2002). Preliminary results of this research has identified that, although passive systems require less maintenance and incur lower operating costs, they are less effective in treating large volumes of acidified water than active dosing systems.

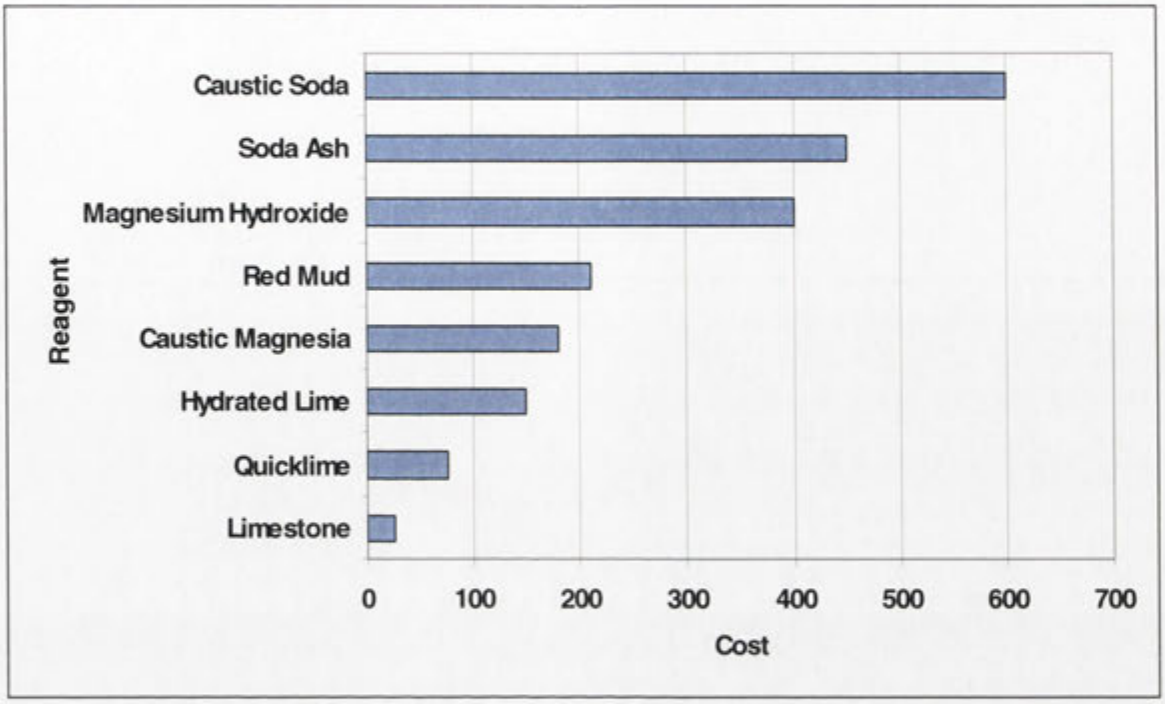


Figure 9.7 Indicative reagent cost per tonne of sulfuric acid neutralised [Source: Clear Solutions Newsletter (2002)].

9.5 Cost Benefits from Tree Plantations

A major impediment to establishing a forestry enterprise is the length of time required before there are any financial gains. This is especially the case for premium timber. However, carbon sequestration may provide an additional incentive for land owners to plant trees and earn additional income from the carbon trading on a long-term basis. Although the Commonwealth Government is at present developing a National Carbon Accounting system which will include commercial forestry, there are a couple of models that are currently available for assessing the costs and benefits derived from carbon trading and timber production. The Rural Industries Research and Development Corporation (RIRDC) has developed the "Carbon Farmer" (www.rirdc.gov.au), a Microsoft Excel spreadsheet, designed to assist farmers in deciding whether it is worthwhile to plant trees for income derived from both the harvested timber and the sequested carbon. The Carbon Farmer allows the user to select a series of options including the price of carbon, length of rotation years between harvests, timber stumpage value, number of commitment periods, the planning horizon, interest rates on money borrowed to establish plantations and plantation establishment costs. The Australian Greenhouse Office "Bush for Greenhouse Field Measurement Procedure for Carbon Accounting" (www.greenhouse.gov.au) has produced a similar accounting package 'CAMFor' specifically for forestry plantations (Richards and Evans, 2000a). A carbon accounting model has also been developed for cropping and grazing enterprises (Richards and Evans, 2000b).

Land owners will only be able to receive carbon credits from trees that have been planted on land previously cleared before 1 January 1990 and does not apply to existing plantations (ANU Forestry, 2000). For the Cudgen Catchment this means that around 4,750 hectares of land could potentially be used for forest plantations assuming all landholders adopt forestry as their primary enterprise. However, land owners may choose not to plant trees for timber or carbon sequestration. Alternatively, they may undertake a combination of tree planting as well as maintaining their existing enterprise. Currently, around 1300 hectares of land is used for cropping and horticultural production. An additional 507 hectares originally used for sugar cane production at the time of the mapping survey (Hamilton, 1998), is now pasture. Since sugar cane was most likely removed after 1 January 1990, land holders would not be entitled to receive carbon credits from tree plantations. However, around 3,000 hectares is grassland cleared before 1990 and which could potentially be used for forest plantations (see Table 8.9, section 8.4.6.4). This would bring the total forest cover from 52% (current cover) to 87% resulting in a reduction in the runoff coefficient from 0.32 to 0.26, which equates to a 14% reduction in surface water flow.

By using the "Carbon Farmer" accounting package, it is possible to examine if it is worthwhile for land owners to engage in tree planting for sequestered carbon and/or timber production. As with most accounting or modelling methods there are of course assumptions that need to be made which may change over time, given the volatility of global markets. There are several assumptions that have been used and these are summarised in Table 9.6. These include the price of carbon, plantation establishment costs, timber stumpage value, set up costs of farming, monitoring, land rental, and the discount rate. The discount rate can be defined as the actual rate that is used to convert the future value resulting from an enterprise into present day values. It can also be defined as "opportunity costs" or the rate of return that might be expected from other business ventures or projects with similar risks. The discount rate is therefore crucial in the determination of the Net Present Value (NPV[1]).

Table 9.6 Main assumptions used in the "Carbon Farmer" and their associated costs or benefits*

Main Assumptions	Costs and Benefits
Plantation Establishment ($/ha)*	**$2,000.00**
Timber Stumpage Value ($/m³)*	**$30.00**
Set up of Carbon Farming ($)*	**$2,500.00**
Carbon Price ($/t/C)*	**$10.00**
Monitoring ($/ha)*	**$10.00**
Land rental ($/ha)*	**$100.00**
Discount rate#	**5% or 7 %**

**Suggested values by RIRDC in $AUD.*

 # The discount rate can vary, however most government departments generally use 7%.

For the purpose of this exercise, three tree models were compared for their net present values over a 60 year period, with two harvests at intervals of 25 years. Since the effect of carbon sequestration will only be measured at the beginning and end of each commitment period, farmers will want their trees to grow as quickly as possible between commitment periods. Therefore in order to get the maximum benefits from tree farming activities, farmers would be likely to plant either extremely fast growing or highly productive eucalyptus plantations. The three tree models used in this exercise fall into either one of these categories, summarised in Table 9.7.

The Carbon Farmer uses an asymmetrical sigmoidal growth function, known as the Gompertz equation, to determine the time course of biomass accumulation in a growing forest. The function is expressed as:

$$W = A * \exp(-b * \exp(-k * t)) \qquad 9.3$$

Where W represents the amount of biomass sequestered (m^3 /ha), t is the time measured in years, A is the asymptotic value with respect to W and b and k are constants that govern

[1]*NPV is "the sum of the present values of each cash flows of each period"[Langfield-Smith et al.,(1998) p18.9]. A period is usually for one year.*

the rate of increase. Basically any tree model could be used only if these parameters are known.

Table 9.7 Description of three tree models used in the analysis.

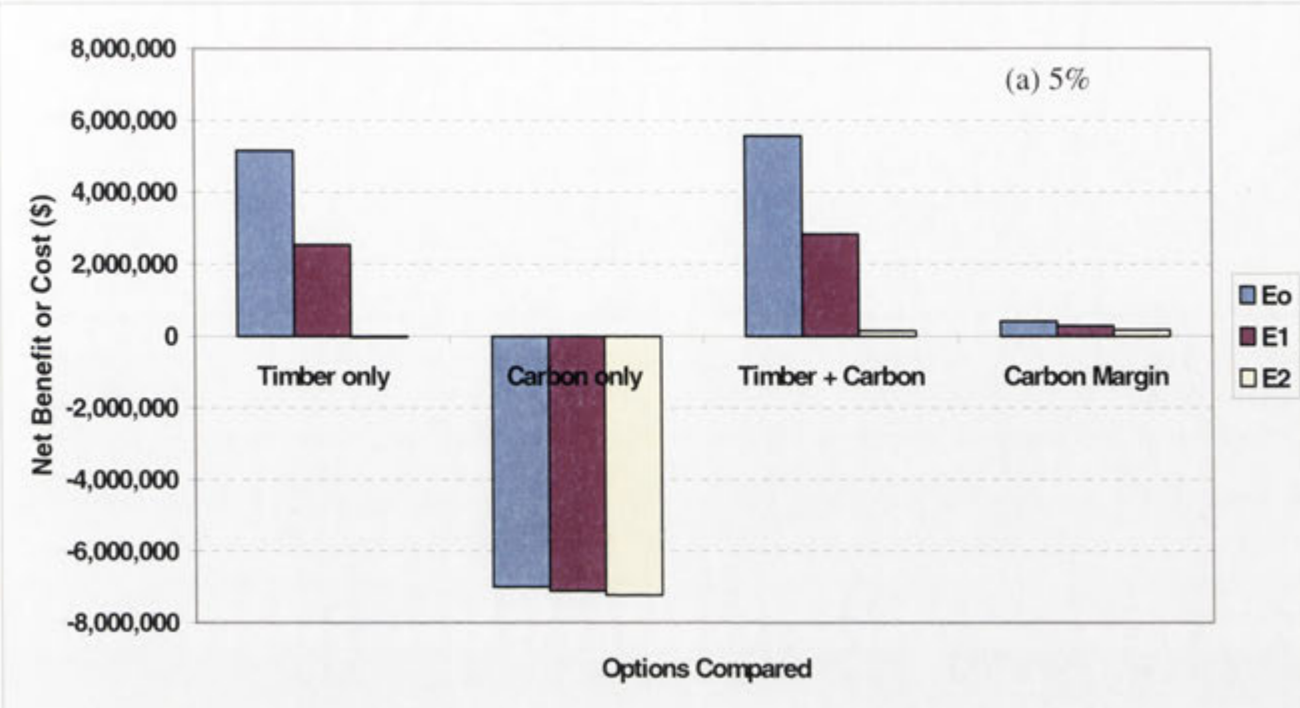
Model Name	**Approximate annual rainfall required**	**Equivalent Mean Annual Increment (m^3 timber/yr)**
E0: Extremely fast growing eucalypts plantation, intensively managed	>1000mm	17
E1:Very high productivity native forest eucalypts and moderate productivity plantations	>800	13.5
E2: High productivity native forest eucalypts and low intensity plantations	>800	10

For this exercise, 3,000 hectares of eucalypts trees were planted in the Cudgen Catchment. The net benefits or costs expressed as net present values for timber production only, carbon production only, timber plus carbon and the carbon margin for all three types of tree models is shown in Figure 9.8. The carbon margin is the NPV of carbon farming plus timber production minus the NPV of timber alone. It can be defined as the added benefit or cost associated with undertaking both carbon and tree farming. Two discount rates 5% and 7%, were also compared for each of three tree models. Australian Commonwealth government departments normally recommend a discount rate of 7%. For all three tree models, there is an additional benefit gained from undertaking both carbon as well as tree farming. It is important to recognise that it is possible to have a positive carbon margin even though the carbon-only farmer makes a net loss. This is because carbon farming shares the same establishment costs as tree farming for timber only. As the results in Figure 9.8 show, planting trees for carbon farming is simply not profitable resulting in an overall net loss. However, this situation may change if the price of carbon is increased, but as it stands, the recommended set price of $AUD10 per tonne of carbon is too low for farmers to contemplate tree farming for carbon alone.

The results show that in order to obtain any real cost benefits from timber only or from "timber plus carbon" farming enterprise, farmers will need to invest in extremely fast growing eucalypt plantations which are intensively managed. The net benefits from this type of enterprise in terms of timber, carbon and biophysical outputs, is summarised in Figure 9.9 a, b and c. The combination of tree farming plus carbon farming will provide farmers with a NPV of approximately $AUD1,000,000 per year or $AUD32,000,000 for each of two harvests over a 60 year period (Figure 9.9a). However, this result is largely determined by the choice of discount rate. As shown in Figure 9.8 a, a discount rate of 5% provides a better return from forest plantations regardless of the type of tree model used. Although carbon trading provides additional cost benefits to tree farming, it should also be mentioned that managers will need to consider the impacts of harvesting plantations on a regular basis, as this will incur carbon penalties every time trees are harvested for their timber (Figure 9.9 b). As shown in Figure 9.9b, the net loss from harvesting is around $AUD6,000,000 for each harvest

Although the basic idea of carbon trading has been widely accepted, there are still many aspects that need to be addressed with respect to the implementation of the Kyoto Protocol. For example, what prices will be paid for permits that allow for carbon dioxide emissions by high polluting industries. Furthermore, there is still some uncertainty as to whether some industrialised countries, such as Australia, will ratify the Kyoto Protocol. Countries that refuse to do so may be excluded from any market in carbon trading.

(a)



(b)

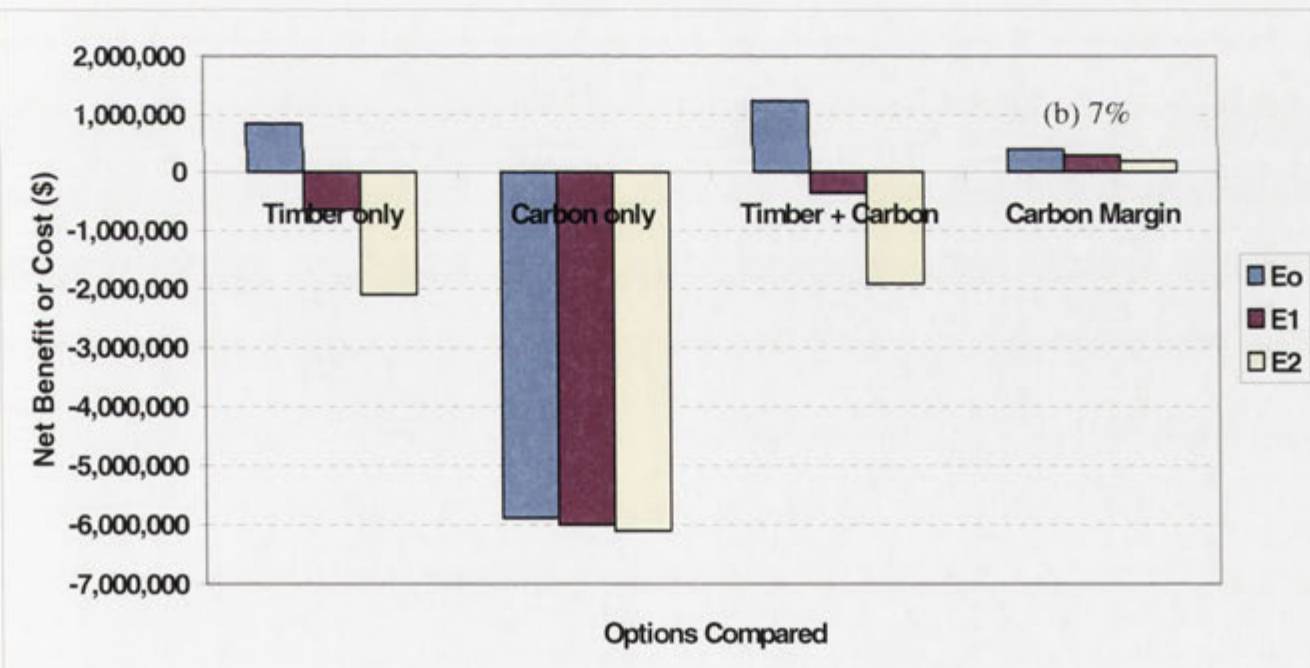
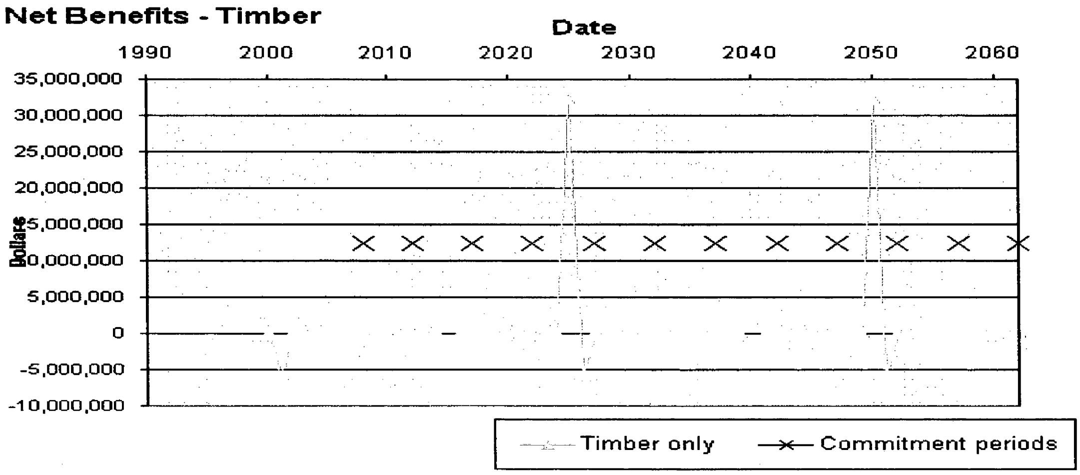
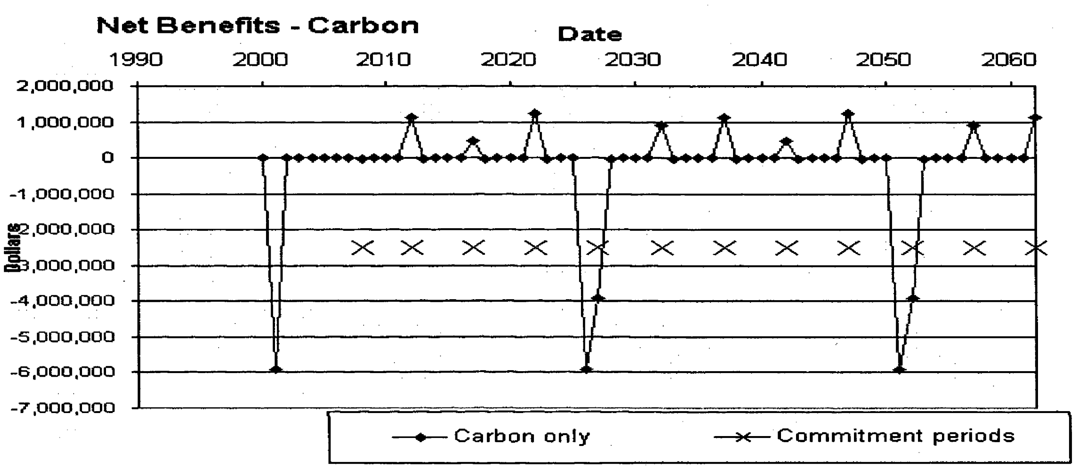


Figure 9.8 The Net Benefits or Costs (measured as Net Present Values (NPV)) for three types of tree models covering an area of 3,000 hectares and when the discount rate is set to (a) 5% and (b) 7%. Values in $AUD.

(a)



(b)



(c)

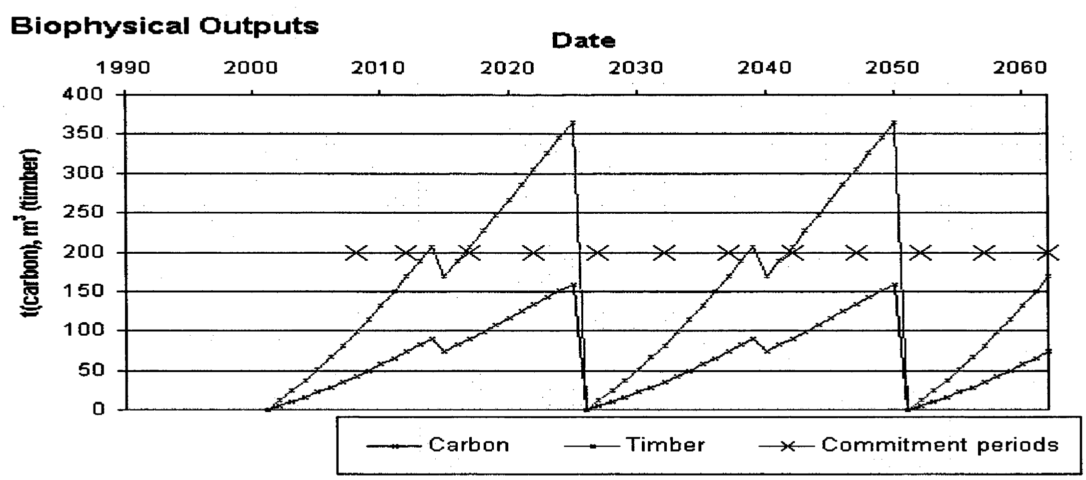


Figure 9.9 The net benefits from (a) Timber production (b) Carbon credits and (c) the Biophysical outputs from an extremely fast growing, intensively managed plantation (model EO). The discount rate is set at 7% over 60 years with two harvest periods.

9. 6 Discussion and Summary

For the Cudgen, the economic, environmental and social costs resulting from years of neglect have been high. There has been considerable loss in productive land from acid scaling and a gradual deterioration in the quality of its water resources, through a lack of appropriate acid sulfate soil land management strategies and sustainable land management practices. The township of Bogangar and the surrounding foreshores of Cudgen Lake, had relied on the lake as an important recreational amenity for the community and tourists, as well as a valuable prawn habitat. Despite the environmental, social and economical consequences, the catchment is still a valuable asset to the community at large. Ecosystems in general are not fully recognised in commercial markets nor are they given an adequate economic representation, comparable to the economic goods and services produced in the catchment and yet they are of fundamental importance to the future of mankind. Based on the Costanza *et al.* (1998) model, the total value from ecosystem services for the Cudgen Catchment is approximately $AUD20 million per year based on an exchange rate of $US=$AUD0.55.

The cost of some remediation strategies, such as capping, is simply too expensive for many catchment management groups and individual land holders. For example, to cap 34% of the lower Cudgen floodplain would incur a remediation cost of between $AUD6 and $AUD22 million dollars, depending on where the capping material is sourced. However, proper identification of "hot spot" trouble areas through detailed soil and ground surveys, means that a much lower fraction of the floodplain could be capped, thus reducing costs. A much cheaper, but still an effective option to capping, is the adoption of a drain reduction strategy in combination with a diversion and levee system.

In some sections of the catchment, beef cattle production has now replaced sugar cane as the predominate agricultural activity resulting in lower gross margins per hectare of agricultural land (Table 9.8). The concept of the user-pays principle for environmental protection and rehabilitation has received mixed reactions from the various industry sectors (Woodhead, 1999). Certain industries, such as the beef and dairy industries, are yet to adopt a policy of self-regulation and best management practice, arguing that there are no economic gains from acid sulfate soil remediation (NWPASS, 1999) and that their industries can least afford to invest in mitigation requirements (Woodhead, 1999). There is an obvious need for these industries to shift their focus towards more sustainable and economic production agriculture with greater emphasis placed on diversification (i.e., tree planting in association with beef farming) for improved productivity returns (see Table 9.8). Timber plantations for both timber production and carbon sequestration is a feasible enterprise provided land owners are prepared to invest in fast growing and highly productive plantations. Tree farming for carbon sequestration and timber production in the Cudgen can provide farmers with a Net Present Value (NPV) of around $AUD32,000,000 for each of two harvests over a 60 year period. This model assumption is based on a discount rate of 7% and 3,000 hectares of an extremely fast growing, intensively managed eucalypt plantation. Timber plantations also offer a better gross margin ($AUD340 per hectare) than beef cattle ($AUD90 per hectare)(Table 9.8) with improved environmental benefits.

Higher productivity returns will allow farmers to invest in ASS management strategies. Perhaps an environment levy, imposed on particular industries and other users of the coastal zone, should be considered as a way of subsidising the costs of maintaining coastal ecosystems and preventing further environmental degradation all of which can be achieved by improved catchment management strategies. It is essential that the value of environmental resources, regardless of how it is measured, must be integrated into main stream policy-making processes.

Clearly, the cost benefit from ecosystem services far exceeds the cost of remediation and treatment of acid discharge over a long-term period. As shown here, the costs of environmental damage from acid discharge can be minimised simply through the adoption of sustainable land management practices. The proposed mitigation strategies discussed here offer a course of action that will ensure economic, social and ecological sustainability through reduced acid discharge and improved water quality. Compared to the true cost of ecosystem services, some of these strategies are cheap and effective at reducing the broader impacts associated with acid discharge. However, it is also important that governments invest more in awareness and communication programs that improve land holders' level of knowledge on acid sulfate soils and the problems they create through poor land management practices. A qualitative investigation has shown that less than 40% of beef and dairy farmers were aware of the environmental impacts of acid sulfate soils (Woodhead, 1999). Improved communication strategies is the next topic of discussion featured in this Thesis.

Table 9.8 Summary of gross margins (in $AUD) for various enterprises and their environmental benefits.

Activity	Gross Margin Per hectare	Benefits	Comments	Source
Sugar Cane	$850	Lower watertable through evapotranspiration, excellent income from crop	More than 70% of farmers laser level	Woodhead, (1999)
Timber	$340	Lower watertable through evapotranspiration, good long-term return on investment	Better return on investment than Beef or Dairy	This research
Beef Cattle	$40-90	Poor returns, no environmental benefits (current situation)	More than 50% of beef farmers believe that ASS are not an issue	Mullen and Kaur, (1999); Woodhead, (1999)
Tea Tree	$3000	Excellent return on investment, however a poor industry response to ASS best management practice	Only 10% of tea tree farmers laser level	Mullen and Kaur, (1999); Woodhead, (1999)

CHAPTER 10
Communication Strategies for Achieving Better Management of Acid Sulfate Soils

Chapter 10. Communication Strategies for Achieving Better Management of Acid Sulfate Soils

10.1 Introduction

The National Strategy for the Management of Coastal Acid Sulfate Soils (NWPASS, 1999) determined that a lack of education and an understanding of the problems associated with acid sulfate soils as significant to achieving better management practices. When stakeholders were asked to identify the major priorities for the future of ASS management, there was overwhelming agreement that "ASSMAC should devote a higher proportion of its investment to improved communication sharing of ASS management information" (NSW Agriculture, 2002). Stakeholders would also like to see more funding spent on education to improve their level of knowledge on ASS, rather than on legislation. Farmers, in particular, also felt that there is often a deficiency in the amount and availability of good advice and information provided to land managers, especially in relation to issues concerning drain and floodgate management (NSW Agriculture, 2001). There is a corresponding need for competent government advisers to provide advice on management options (ASSMAC, 1999a) and to disseminate positive information to the media regarding their concerns and actions with respect to acid sulfate soil management issues (ASSMAC, 1999a).

Another major concern raised by farmers and community groups is the need for clearer technical information relating to ASS management rather than the continued broadscale awareness raising programs which have had little impact on addressing the particular problems caused by ASS (NSW Agriculture, 2002). There is a common belief amongst farmers that greater knowledge about acid sulfate soils is not necessarily resulting in better on-ground management activities and that there is a real need for an effective process of technology and information transfer (NSW Agriculture, 2002). Stakeholders strongly believe that information and technology transfer should be an integral component of all research projects (NSW Agriculture, 2002). It has also been suggested that " science information by electronic-mail (e-mail) would be beneficial", including the development of an e-mail network between researchers, government organisations and stakeholders (NSW Agriculture, 2002).

Clearly, it is useful for stakeholders to access information without too much detailed technical jargon, but, because the management of acid sulfate soils transects the jurisdiction of many government and non-government agencies (NGAs) there is uncertainty as to how information can be shared, accessed and disseminated to those concerned. And, it is still a challenge as to how technical and non-technical information should be presented and whether guidelines should be implemented to assist in the transfer of information from researcher to land manager. Although ASSMAC conducted regular workshops and field days to demonstrate the latest research results and to promote active discussion and problem solving on a range of ASS issues, there a real need for a more centralised approach to information management and dissemination.

There is the potential to use modern telecommunications software to display and manage information for decision and policy making. The Internet allows many organisations and community groups the ability to disseminate as well as access information through the World Wide Web. One fundamental problem facing many organisations when accessing so much information available on-line, is the method by which electronic information is sorted and new information is stored and managed.

To improve the flow of information between stakeholders, community groups and organisations, the National Strategy for Acid Sulfate Soils (NWPASS, 1999) aims to establish a "framework for national communication" and the development of a web site to provide ASS technical, funding and management information. Unfortunately, the National Strategy does not provide any mechanism for the development and implementation of such a framework for improved communication flow on a national level.

This chapter examines the role of information and decision supports systems and their potential role in the management and planning activities associated with acid sulfate soils. The two systems described in this chapter, demonstrate the effective use of Information and Communication Technology (ICT) in acid sulfate soil management and provides the framework for improved communication at the national level. The first is the Electronic Content Management System (ECMS) for information and document management. The second system is a Geographic Decision Support System

(GDSS) developed primarily for researchers and land managers in the McLeods Creek Catchment of the Tweed Valley.

10.2 Information Management

10.2.1 Information Sourcing and Information Users

The Commonwealth Government (Commonwealth of Australia, 1996, p1-6) has identified the main user groups of information -

1) *"the general public and specific community interest groups and sectors;*
2) *government decision-makers and policy analysts at Commonwealth, State, Territory and local levels;*
3) *cultural and natural resource planners and managers;*
4) *scientists;*
5) *primary, secondary and tertiary educational institutions;*
6) *industry groups;*
7) *print and electronic media;*
8) *international agencies"*

The hierarchy of information requirements (Figure 10.1) can vary between groups depending on their specific needs. Environmental planners and scientists, for example, often require very detailed information, whereas, the general public generally prefer an overview or "snapshot" of the problems or issues. There is a general expectation from all these groups that the information provided should not only be current but is accurate and easily accessible (Commonwealth of Australia, 1996). The development of any communication strategy must, therefore, meet the needs of these different groups through the provision of both technical and non-technical information that is accurate and sufficiently detailed.

Farmers, council planners, and government bureaucrats require up-to-date information on land use and attributes; changes to policies and regulations; community concerns and issues and on-ground activities such as environmental monitoring and remediation works. This range of information is collected from several sources including researchers, local government inspectors, community groups, as well as land owners and farm managers. Although information is essential for sound decision-making, the sheer volume of information is increasing and the form in which information is made available can vary.

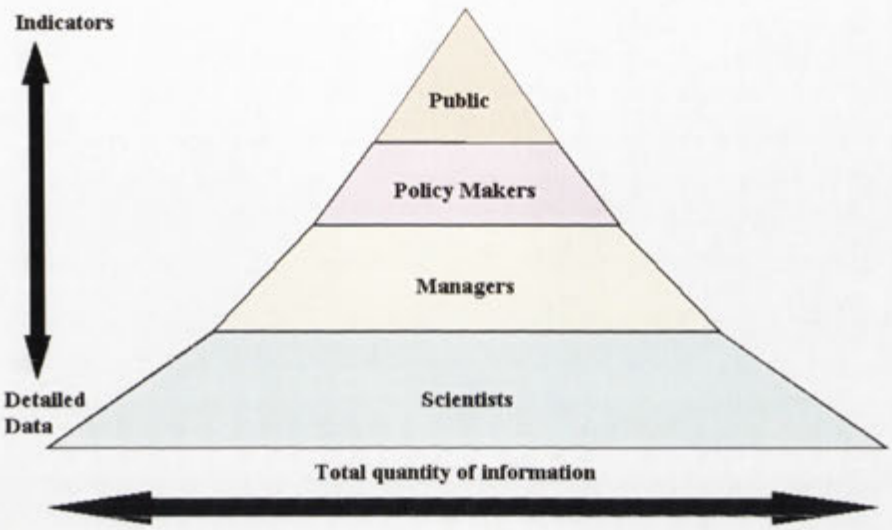


Figure 10.1 Hierarchy of information requirements (Source: Commonwealth of Australia, 1996, p1-6).

Access to information through electronic means is becoming more common as telecommunication and information technology improves the speed by which information can be down-loaded to personnel computers. It is highly likely that as computer technology becomes more powerful and more accessible to people, not only in the developed world but also in the 'developing world', the use of electronic media to disseminate information will become more common place.

Information on acid sulfate soils can be sourced electronically or via print media. The quarterly newsletter "ASSAY", which is distributed by the NSW Department of Agriculture, provides information on events and management issues relating to ASS. Various State Government departments also publish technical reference manuals but these are generally "one-off" publications distributed to farming and community groups. Also, most government departments provide these types of publications in electronic format via their web sites. A 1998 ASSMAC (Woodhead, 1999) survey examined where the major industry stakeholder groups sourced their information and advice on ASS. The results of this survey revealed that the sugar cane farmers obtain

71% of their information from their industry association compared with 66% for tea tree and 9% for beef cattle. Based on these results, it is clear that some industry associations are an important source of information for stakeholders and should therefore represent an important component in the development of a communication network strategy. For all the industry groups that participated in the survey, it was found that information on ASS was mostly sourced from print media such as newspapers (40%), colleagues (30%) and television or radio (30%). Government agencies were considered to be an important source of information for the dairy and beef industries. Government departments preferred to disseminate important information on ASS via printed articles, television and radio. However, given the rapid expansion and interest in the Internet, there are no recent statistics available on which is now the most preferred option.

10.2.2 Information Dissemination and Management by Electronic Communications

The Internet, a world-wide digital network of computers linked by an array of data transmission devices such as satellite, fibre optic, co-axial and telephone communication lines, is now widely used. The transfer of data involves using standard coupling protocol known as either Transmission Control Protocol (TCP) or Internet Protocol (IP). Access to the Internet is via Personal Computer which is connected to one or more of these transmission devices, discussed above.

The Internet performs a number of functions. These include:

- Providing information including 'real time' information,
- Serves as a communication tool in the form of electronic mail or discussion forums,
- Transferring large files through a File Transfer Protocol (FTP) and
- Running programs from remote locations.

Access to the World Wide Web is through a 'web server' from remote locations using a 'web browser'. Data, stored on the web server, is written in hypertext format such as Hypertext Mark Up Language (HTML), Java or Hypertext Preprocessor (PHP), is transformed into web pages for viewing.

The Internet has revolutionised the way individuals and organisations access and manage information. It is commonly used as a front-end for a variety of environmental applications including database access (Doorn and Eliens, 1995) and for displaying geographic information (Boston and Stockwell, 1994). Despite the advantages that the Internet has provided for people in environmental management, there is a pressing need for any organisation, group or individual to effectively manage the flow of information that is being accessed. The world wide web has several powerful search engines such as "Google.com" or "Altavista.com" that search the Internet for registered sites on any topic of interest simply by using the key word search function. There are numerous web sites and information relating to acid sulfate soils. When the key words " acid sulfate soils" are entered into the Google.com search engine, for example, the system locates 3,450 sites with these words in the topic.

The electronic information that is gathered by search engines constrains the user to access appropriate information in a systematic way without the need to view hundreds of sites individually. One way around this problem is through the development of a portal site. A portal site is a directory of selected sites specifically targeted at a particular audience(s). It ensures that relevant sites are selected and indexed in a systematic format, usually using a carefully designed classification and database system. Various organisations such as the European Centre for Nature Conservation have developed their own portal sites centred around a database and classification system (Delbaere *et al.*, 1995). This system indexes information from other sites according to the topic and subject matter such as education, biodiversity, funding sources, mapping and research projects.

10.2.2.1 The Importance of Metadata

One of the most important requirements in the development of any electronic information system is the quality of the metadata. Metadata can be defined as data about data and is a mechanism for describing electronic information. For example, typical metadata about a particular document might include:

- < Date Created>
- <Author>
- <Subject>
- <Description>
- <Copyright>

The development of a standardised classification system is important as it provides a basis for creating suitable metadata that allows for the classification and indexing of electronic information. Furthermore, it also permits the rapid retrieval of information through improved search function capabilities thereby allowing documentation searches to be conducted using more than one parameter such as author, subject, description or date. Advanced search function capabilities are possible if there are adequate metadata available. Attempts are now under way to develop international metadata standards that can be adapted to suit a range of different disciplines. The Dublin Core (http://www.dublincore.org) initiative, for example, supports the concept of standardising metadata and is actively developing specialised vocabularies to describe a range of information resources. The Australian Government has also established standards based upon those established by the Dublin Core. The National Archives of Australia http://www.naa.gov.au/recordkeeping/gov_online/agls/summary.html) is the agency responsible for the maintenance of the Australian Government Locator Service (AGLS) metadata standard, developed for commonwealth government sites. State and local governments are not as pro-active as their commonwealth counterparts in this area.

10.2.2.2 Information Quality Control

Currently, there are few quality control measures available for information on the Internet. There is no guarantee that scientific articles available on line have received the same level of scrutiny as scientific articles published in printed journals. Quality control in journals is maintained through peer review – the same could be achieved for electronic information. The development of a portal site can ensure to some degree that standards of quality control are maintained through a central administrator whose specific role is to ensure that on-line material is carefully scrutinised for quality of content and accuracy.

10.3 Level of Awareness of Acid Sulfate Soil and the Need for Better Communication Strategies

There is at present no reliable mechanism in place that can accurately measure the level of understanding and awareness of ASS issues. An understanding of social attitudes and knowledge base levels regarding ASS is a fundamental requirement for the development of a sound communication framework. Woodhead (1999, 2003) carried out two surveys which benchmarked the level of knowledge, attitude and awareness of ASS for ASSMAC in three key areas, industry, government and excavators. Attitude was included in both surveys because it determines the behaviour of an individual.

The 1998 survey showed that the level of awareness of acid sulfate soils and the problems they cause, varied between industry groups. The sugar cane industry was more aware of the problems associated with ASS than any other industry group. However, since the 1998 survey, most industry groups showed a marked change in attitude and knowledge about acid sulfate soils (Figure 10.2), however, beef farmers were still antagonistic towards conservationists, and local councils (Woodhead, 2003). The 1998 and the 2002 survey showed that the industry associations played a crucial role in highlighting the importance of acid sulfate soil management and awareness. However some associations were more active in providing relevant information to their industry members on ASS issues and management practices than others.

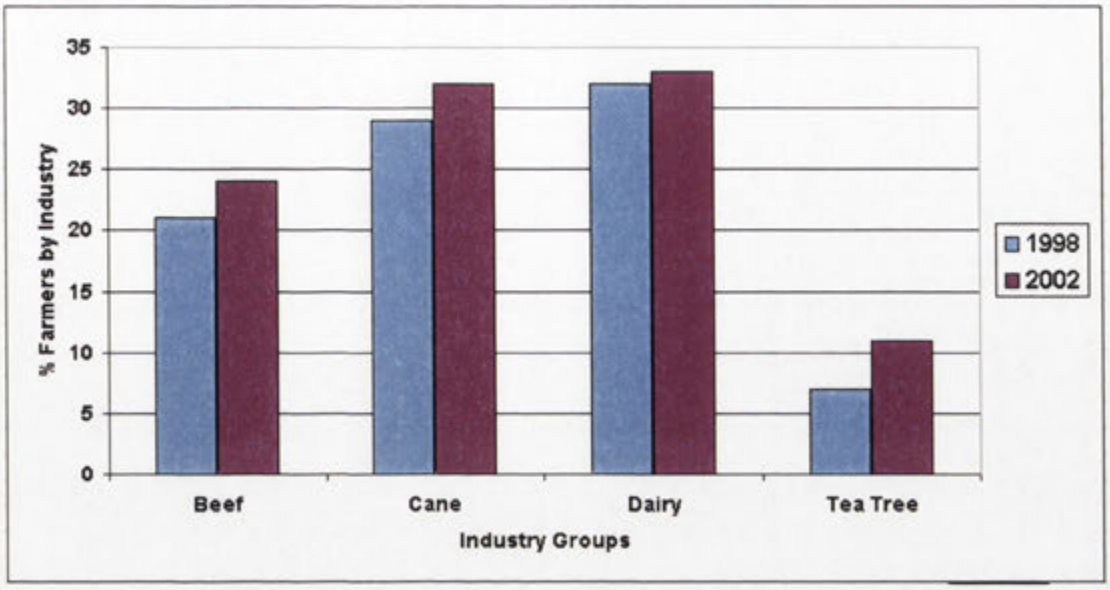


Figure 10.2 Changes in attitude and knowledge about ASS by farmers surveyed in 1998 and again in 2002. Values expressed as average years in industry (Source: Woodhead, 1999 and Woodhead, 2003).

10.4 An Electronic Content Management System (ECMS) for Information Resource Management

An understanding of the above issues is fundamental to the development of a broad-based communication framework proposed in the "National Strategy for the Management of Acid Sulfate Soils" (NWPASS, 1999). In the National Strategy, reference is made to the establishment of a web site that will provide "ASS information, particularly technical, management and funding information" to land and catchment managers, and other stakeholders (NWPASS, 1999). However, most Government departments or agencies involved in acid sulfate soil issues already provide information on their sites relating to legislation, technical information and funding opportunities. Furthermore, because acid sulfate soils are not just confined to one jurisdiction, there are many other organisations or agencies at the local, state and commonwealth level that play an important role in the management and rehabilitation of these coastal landscapes. For example, community based groups, such as Coastcare and Landcare, play an active role in this area. With so many different groups involved in the management of these soils there is a need to develop a web portal that would assist in the coordination and management of electronic information from various sources. In this work an Electronic Content Management System (ECMS) for coastal catchments with acid sulfate soils was developed and the portal site cassdirectory.org was established.

The cassdirectory.org site is effectively an ECMS for the dissemination and retrieval of information relating to coastal acid sulfate soils. The aim of the cassdirectory ECMS is not to duplicate existing information from other web sites but to provide a well-structured portal site that can assist users to access the right information far more effectively than by using standard search engines such as Google. The system also has a database, which allows for the publishing, updating and archiving of information such as scientific publications and reports.

A Canberra-based company, Millpost Technologies Pty Ltd, produced the ECMS software used to develop the site. The advantage with the ECMS software is that it is licensed as open source software. Open source works on the premise that the components (i.e., code) of a piece of software can be copied, altered or modified to suit a particular application, thus improving its overall functionality. The software should be distributed free of charge via the Internet. Furthermore, according to Open Source definition "the licensee cannot restrict any party from selling or giving away the software as a component of an aggregate software distribution containing programs from several different sources".
(http://www.opensource.org/docs/definition.php)

The cassdirectory ECMS has several components and these are summarised in Figure 10.3. The most important components of the system for the management and retrieval of electronic information include the database and directory. These two components were developed with the user and administrator requirements in mind. The directory component uses a cascading classification system to assist the user in locating information by category (Figure 10.4). The development of the classification scheme allows for the indexing of new and existing information. The categories used in the construction of the cassdirectory ECMS were modelled on those agencies (government and non-government) and industry groups most affected by acid sulfate soils or those playing a leading role in the management and rehabilitation of acid sulfate soil landscapes. The roles and responsibilities of these groups and agencies were previously discussed in Chapter 2, section 2.3.

The classification system includes the primary categories of "Industry" groups, "Research Groups and Activities", "Community and Advisory Groups", "State", "Federal" and "Local" Government agencies, "ASSAY Newsletter", major "Events" and "Management". The category "Research Groups and Activities" lists the major groups involved in acid sulfate soils research. These groups are broken down further to reveal their projects, on-line reports and publications. The "Hot Spot" Remediation category has been sub-divided to include the remediation sites. Since advice on acid sulfate soil management was seen as an important issue by some industry groups, the category "Management" was included in the classification scheme. Under this heading were included the categories of "Rehabilitation", "Legislation", "Policy" and "Technologies". The classification system and their respective categories are shown in Figure 10.4.

The cassdirectory.org site has an administration component for the management and up-loading of information to the site. This section is effectively the database of information relating to each category. The administration server component of the ECMS consists of the three management domains. These include the document manager, media manager and user manager. The document manager allows the site administrator to change or add content to the site (Figure 10.5) including metadata (Figure 10.6).

An internal web crawler can be used to search other web sites for key words relating to acid sulfate soils and indexes these under their appropriate headings. The web crawler would also notify the administrator of broken links. One important advantage with the cassdirectory ECMS is that the administration of the site does not require any knowledge of complex coding such as HTML, Cold Fusion or PHP. This particular feature also allows for the inclusion of discussion boards for sharing and networking using a member's 'login' page.

Figure 10.3 Components of the Cassdirectory ECMS web site.

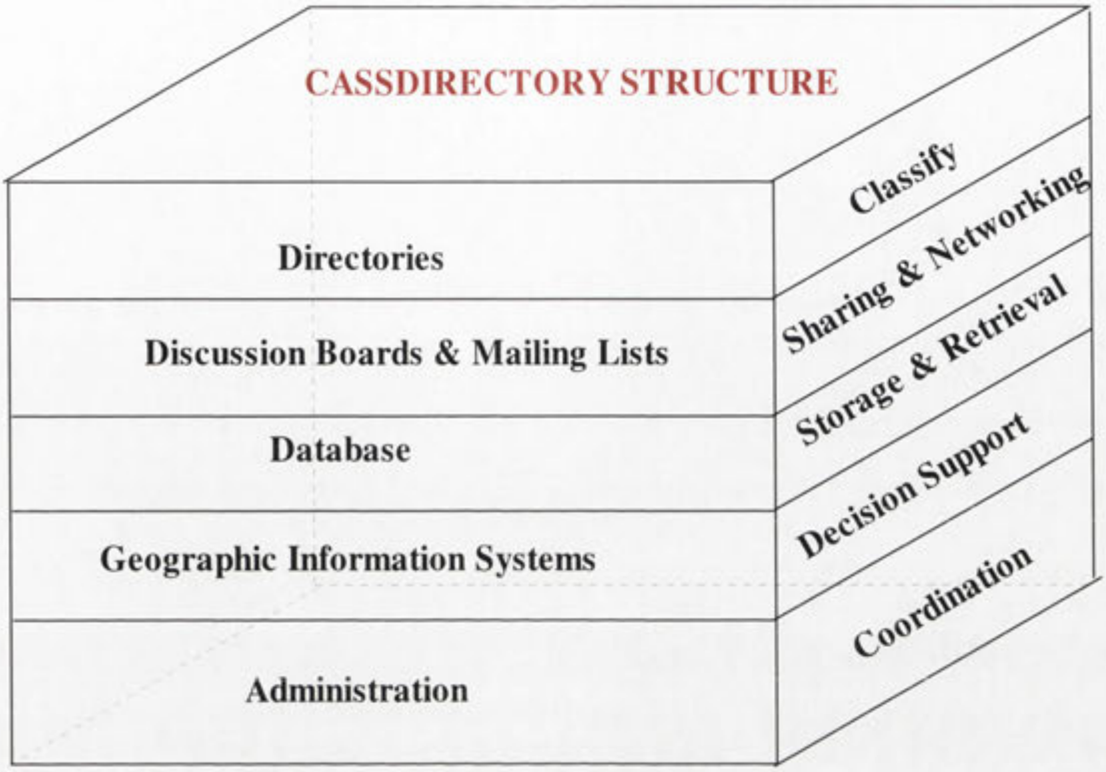
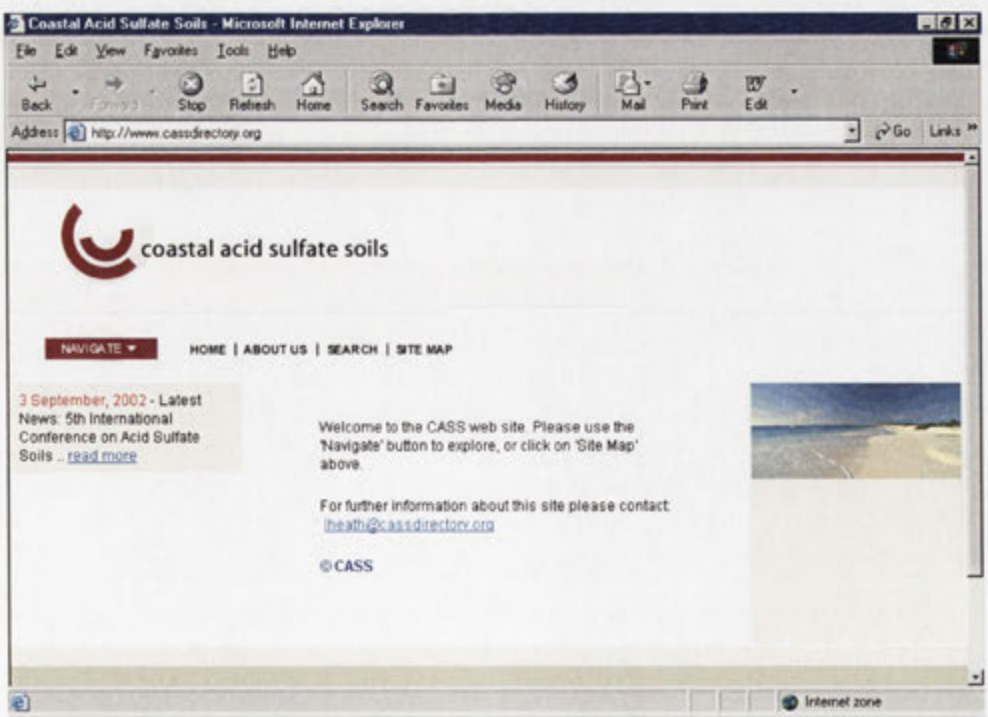
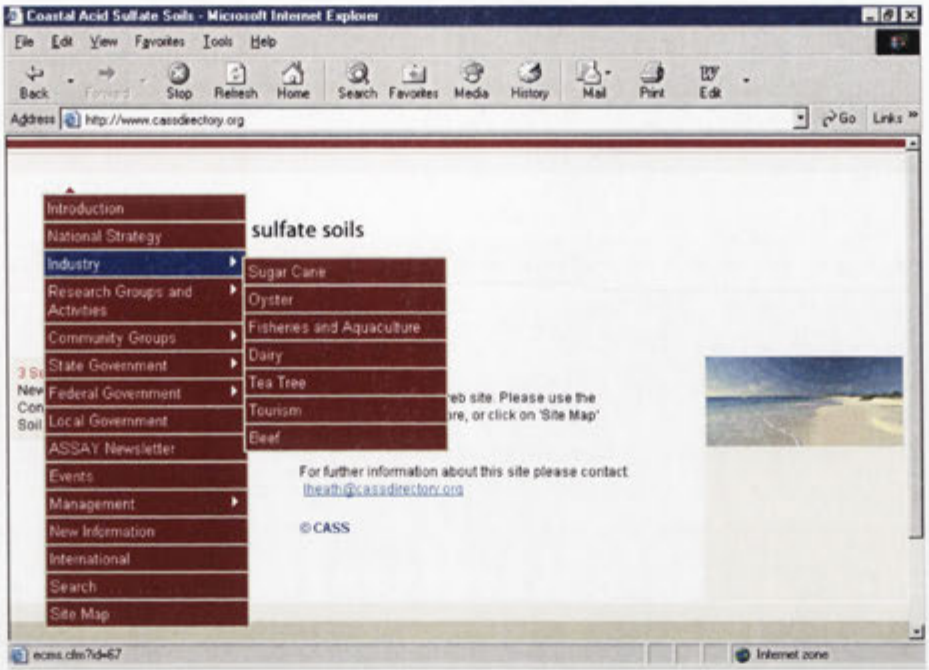
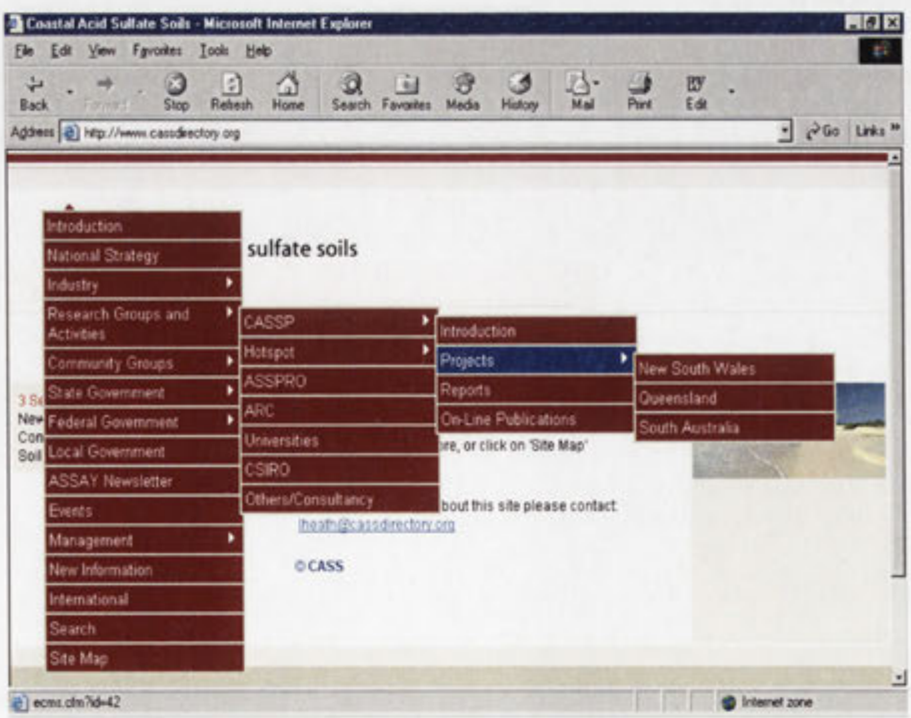
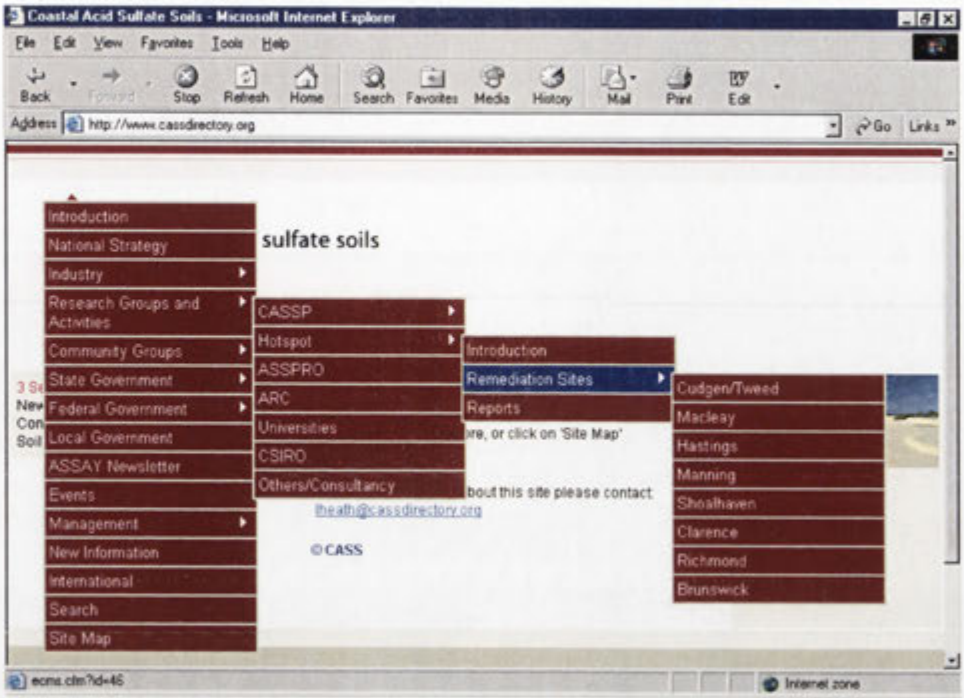


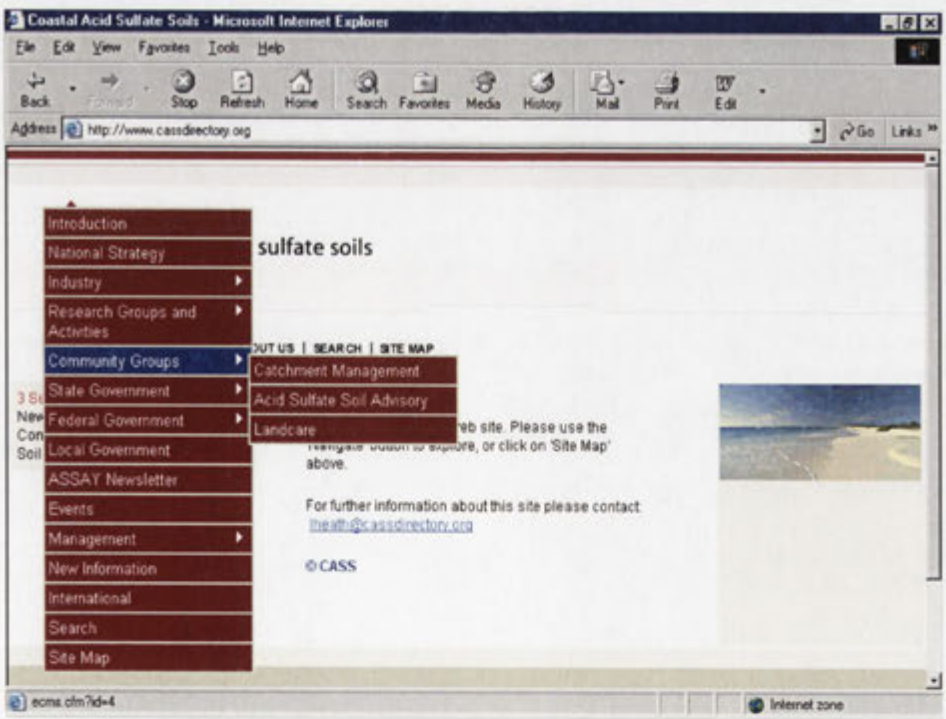
Figure 10.4 User front-end to the system including the cascading classification system.

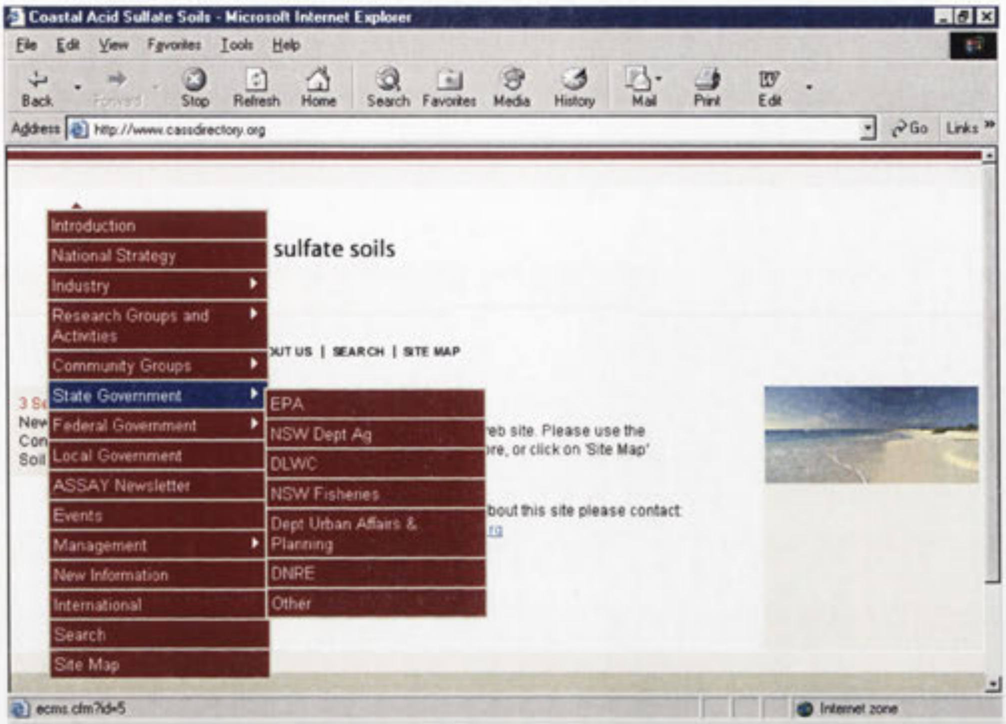



Coastal Acid Sulfate Soils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Forward Stop Refresh Home Search Favorites Media History Mail Print Edit
Address http://www.cassdirectory.org
Go Links
Introduction
National Strategy
Industry
Research Groups and Activities
Community Groups
State Government
Federal Government
Local Government
ASSAY Newsletter
Events
Management
New Information
International
Search
Site Map
Sugar Cane
Oyster
Fisheries and Aquaculture
Dairy
Tea Tree
Tourism
Beef
sulfate soils
eb site. Please use the
re, or click on 'Site Map'
For further information about this site please contact
lheath@cassdirectory.org
© CASS
ecms.cfm?id=67
Internet zone

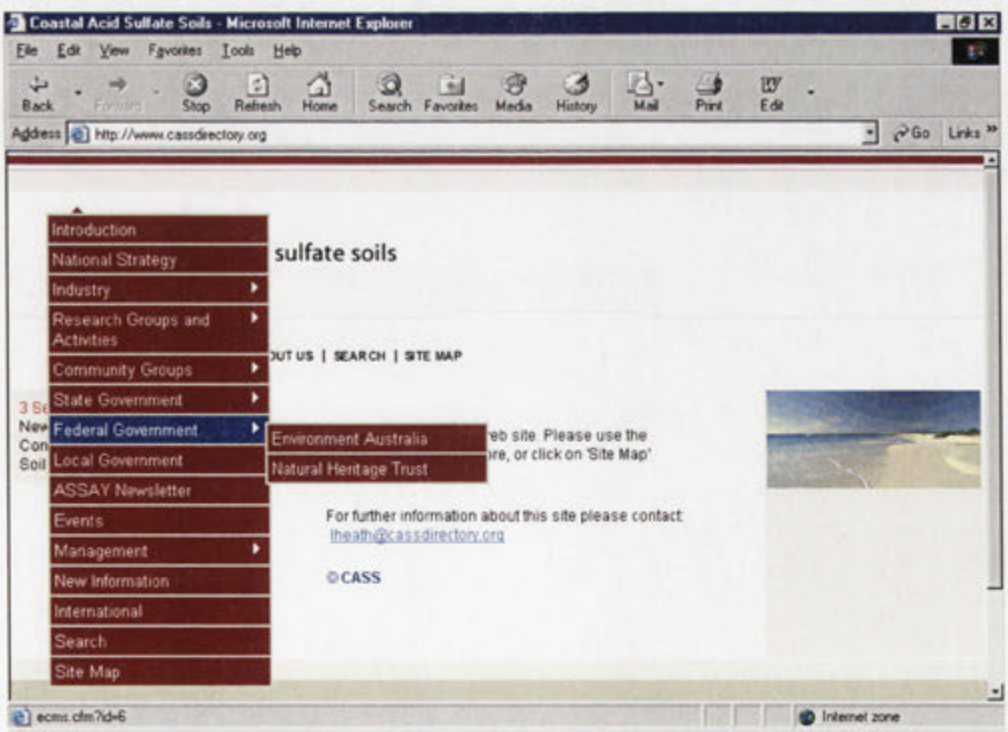

Coastal Acid Sulfate Soils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Forward Stop Refresh Home Search Favorites Media History Mail Print Edit
Address http://www.cassdirectory.org
Go Links
Introduction
National Strategy
Industry
Research Groups and Activities
Community Groups
State Government
Federal Government
Local Government
ASSAY Newsletter
Events
Management
New Information
International
Search
Site Map
sulfate soils
CASSP
Hotspot
ASSPRO
ARC
Universities
CSIRO
Others/Consultancy
Introduction
Projects
Reports
On-Line Publications
New South Wales
Queensland
South Australia
re, or click on 'Site Map'
bout this site please contact
lheath@cassdirectory.org
© CASS
ecms.cfm?id=42
Internet zone


Coastal Acid Sulfate Soils - Microsoft Internet Explorer
http://www.cassdirectory.org
sulfate soils
Introduction
National Strategy
Industry
Research Groups and Activities
Community Groups
State Government
Federal Government
Local Government
ASSAY Newsletter
Events
Management
New Information
International
Search
Site Map
CASSP
Hotspot
ASSPRO
ARC
Universities
CSIRO
Others/Consultancy
Introduction
Remediation Sites
Reports
Cudgen/Tweed
Macleay
Hastings
Manning
Shoalhaven
Clarence
Richmond
Brunswick
lheath@cassdirectory.org
© CASS

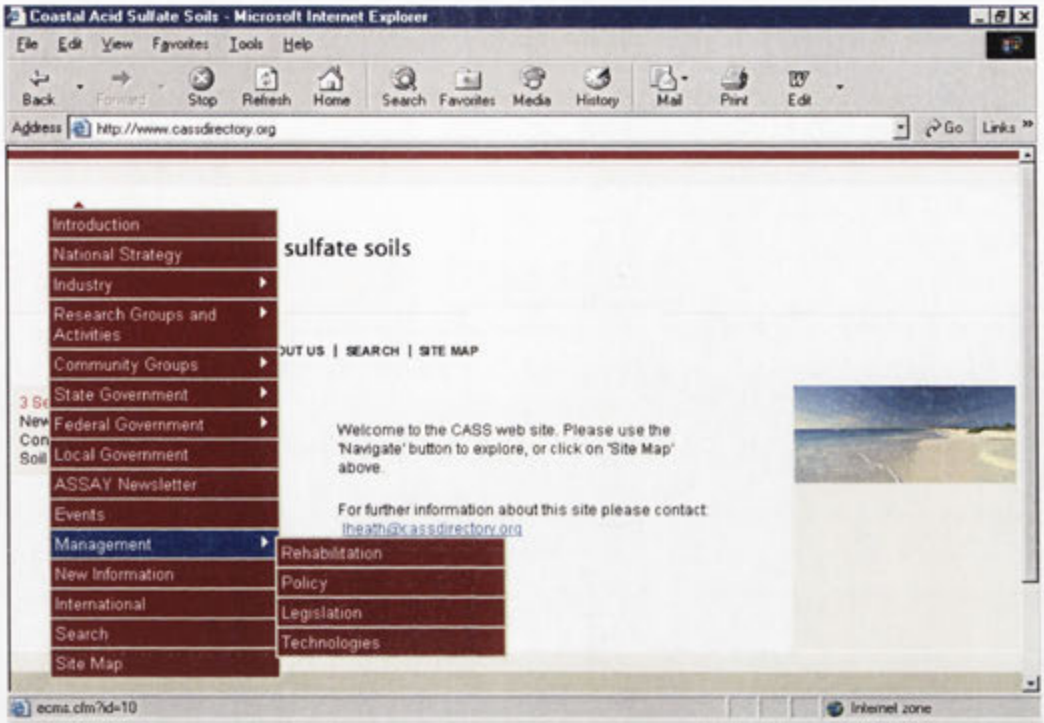

Coastal Acid Sulfate Soils - Microsoft Internet Explorer
http://www.cassdirectory.org
sulfate soils
Introduction
National Strategy
Industry
Research Groups and Activities
Community Groups
State Government
Federal Government
Local Government
ASSAY Newsletter
Events
Management
New Information
International
Search
Site Map
Catchment Management
Acid Sulfate Soil Advisory
Landcare
For further information about this site please contact
lheath@cassdirectory.org
© CASS



Coastal Acid Sulfate Soils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Forward Stop Refresh Home Search Favorites Media History Mail Print Edit
Address http://www.cassdirectory.org
Go Links
Introduction
National Strategy
Industry
Research Groups and Activities
Community Groups
State Government
Federal Government
Local Government
ASSAY Newsletter
Events
Management
New Information
International
Search
Site Map
sulfate soils
UT US | SEARCH | SITE MAP
EPA
NSW Dept Ag
DLWC
NSW Fisheries
Dept Urban Affairs & Planning
DNRE
Other
eb site. Please use the
re, or click on 'Site Map'
bout this site please contact
ecms.cfm?id=5
Internet zone



Coastal Acid Sulfate Soils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Forward Stop Refresh Home Search Favorites Media History Mail Print Edit
Address http://www.cassdirectory.org
Go Links
Introduction
National Strategy
Industry
Research Groups and Activities
Community Groups
State Government
Federal Government
Local Government
ASSAY Newsletter
Events
Management
New Information
International
Search
Site Map
sulfate soils
UT US | SEARCH | SITE MAP
Environment Australia
Natural Heritage Trust
eb site. Please use the
re, or click on 'Site Map'
For further information about this site please contact
lheath@cassdirectory.org
©CASS
ecms.cfm?id=6
Internet zone


Coastal Acid Sulfate Soils - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Forward Stop Refresh Home Search Favorites Media History Mail Print Edit
Address http://www.cassdirectory.org
Go Links
sulfate soils
Introduction
National Strategy
Industry
Research Groups and Activities
Community Groups
State Government
Federal Government
Local Government
ASSAY Newsletter
Events
Management
New Information
International
Search
Site Map
Rehabilitation
Policy
Legislation
Technologies
UT US | SEARCH | SITE MAP
Welcome to the CASS web site. Please use the 'Navigate' button to explore, or click on 'Site Map' above.
For further information about this site please contact
lheath@cassdirectory.org
ecms.cfm?id=10
Internet zone

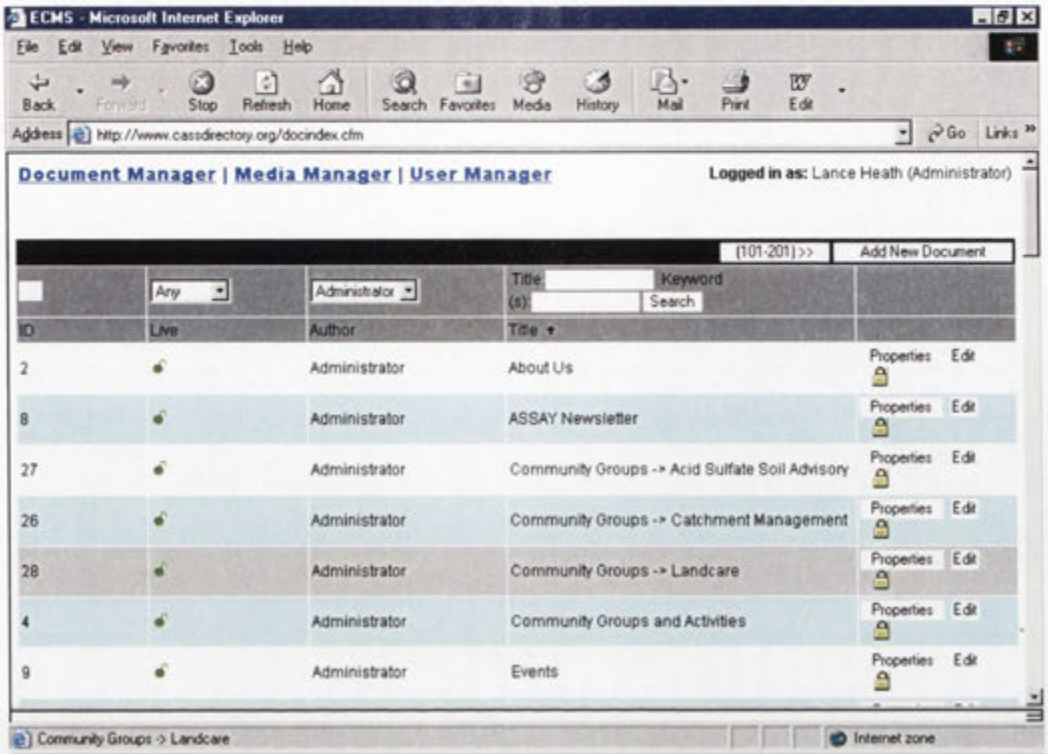


Figure 10.5 Administration server side component of the ECMS.

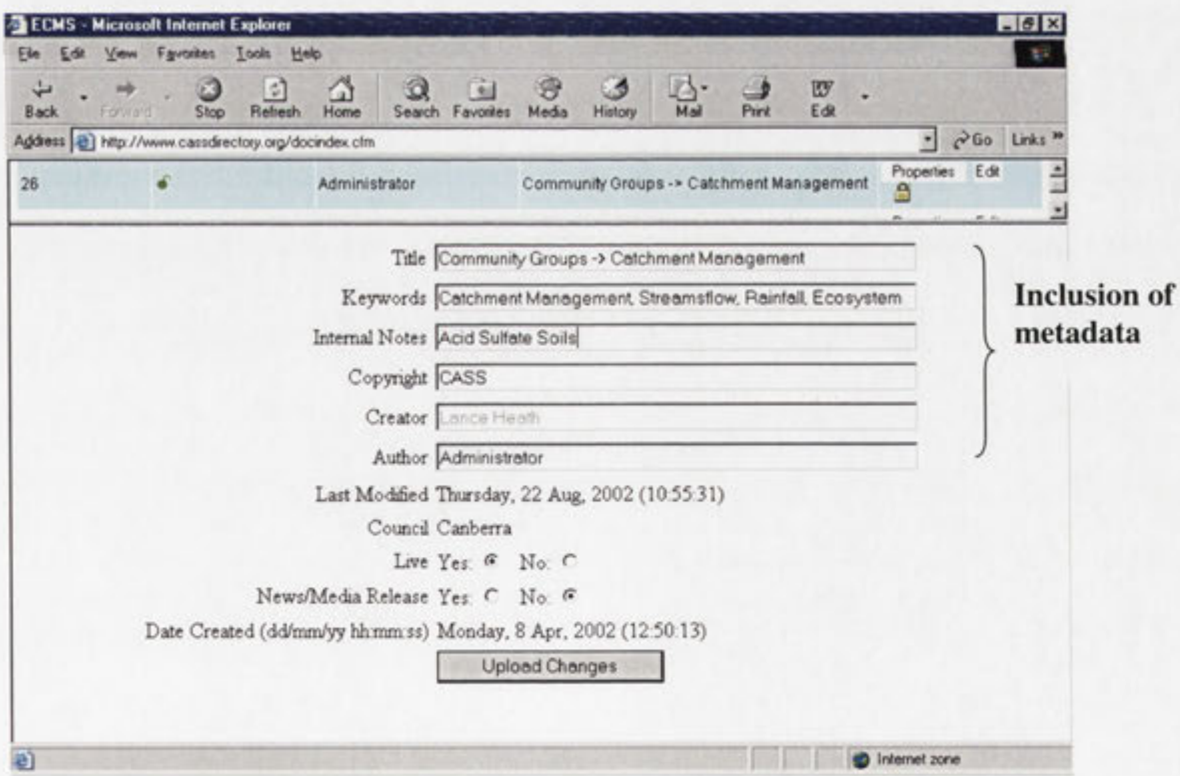


Figure 10.6 Process used for the inclusion of metadata.

10.5 Decision Support Systems for Environmental Management

Decision-makers working in environmental management are continuously faced with the problem of being able to predict potential changes in the environment in response to factors such as land management decisions and climate. Although monitoring programs are important for measuring environmental change, they often require the appropriate analytical or modelling systems that allow decision-makers to take appropriate steps to rectify current or potential environmental problems. These systems are generally referred to as Environmental Decision Support Systems (EDSS) (Frysinger, 1995; Guariso and Werthner, 1989). EDSS provide a useful role when used to predict long-term impacts associated with land changes, however they have their limitations in modelling changes using real-time data.

Many EDSS have been developed for a range of different environmental applications. The most common type is the Spatial Decision Support System (SDSS) which uses a combination of different components including analytical tools to conduct data searchers; a geographic or spatial database; "decision models" to examine the impacts of scenarios and a user interface (Densham, 1991). A GIS can therefore be considered as part of a decision support system, however, the SDSS uses certain functions of a GIS combined with software tools that are specifically developed to assist in decision making (Clarke *et al.,* 2001). The hydrological modelling system developed in this work (Chapter 4) is a good example of a SDSS. However, it was not designed to be used in conjunction with relational database systems to display on-line modelling results. Most decision support systems generally have a strong focus on the use of query and visualisation tools to communicate and help in the interpretation of data (Leung, 1997).

There are many large organisations that have adopted on-line decision support systems as an integral part of their planning and emergency response activities. For example, a recent on-line decision support system is the CSIRO "Sentinel Bush Fire Mapping Tool" (http://www.sentinel.csiro.au/mapping/viewer.htm). The Sentinel uses a geographical map interface to display fire location data across the entire continent of Australia. The system is designed primarily for emergency service personnel and uses satellite technology and web based mapping tools to locate the position and movement of fires and their potential risk to the community and property. Another example is the RODOS (Real Time On-line Decision) system which was initiated by several European nations in response to previous environmental catastrophes, such as the Chernobyl nuclear disaster of 1986 (Ehrhardt *et al.,* 1997). Another system developed at a cost of around $US7 million is the Pacific Regional Management Information System (PREMIS) which uses a GIS module known as the Integrated Emergency Management Information System (IEMIS) which has been integrated with a modelling module known as an Integrated Baseline System (IBS) (Conway, 1997). The system uses the internet to map flood levels and track hurricane movements and calculates the best transport options for evacuation procedures. The Australian Bureau of Meteorology http://mirror.bom.gov.au/weather/radar/ also employs an on-line geographic interface to display radar images of rainfall intensity across the continent. Radar images are up dated every ten minutes providing local authorities and the general public with warnings of impending danger from approaching storms.

10.5.1 Visualisation as a Communication Tool

McCormick *et al.* (1987) defines visualisation as "a tool or method for interpreting image data fed into a computer for generating images from complex multi-dimensional data sets". The ability to geo-reference or display spatial information is a fundamental requirement in certain disciplines such as geology, hydrology, environmental modelling, meteorology and ecology. These disciplines rely on visualisation as an integral component of their work. The need to display information and data in a clear and precise format for decision support, is becoming more recognised by researchers and policy makers throughout the world. Policy makers are now using "visual displays" to assemble vast quantities of information for decision support (Burgess, 2002).

Although good data visualisation enhances the ability of the user to understand and interpret the data, it is also important to recognise the factors associated with the development of good visualisation techniques. Ideally, the use of these techniques should take into consideration the data characteristics (Roth and Mattis, 1990) and for what purpose it will serve (Andrienko and Andrienko, 2001). Early decision-based systems recognised the need to create graphical visualisation based on the underlying data characteristics (Mackinlay, 1986), whereas Casner (1991) showed that the same information could be presented in different formats to support an array of different tasks.

It is now relatively easy to produce high quality and sophisticated graphics and other visual output displays from just about any data set. Tufte (1983), recommends that before any statistical treatment of data is considered, it is essential that the raw data be first displayed in either graphical or in some other visualised format. Good visualisation can assist statistical analysis and interpretation of data with respect to errors and anomalies as well as provide useful information on the characteristics of the distributions such as skewness or dispersion. Relationships between individual parameters or variables can also be determined relatively quickly using graphical formats.

10.5.2 Access to Spatial Data for Communication and Decision Support

There are organisations and groups that are actively involved in supporting research into geo-referenced visualisation systems for the presentation of spatial and non-spatial data to the global community. The Commission on Visualisation and Virtual Environments of the International Cartography Association (CVVEICA) (http://www.geovista.psu.edu/sites/icavis/) promotes the use of maps as tools for decision support and data analysis (MacEachren 1994; Andrienko and Andrienko, 2001). The Commission also places a strong emphasis on developing software and computer systems that facilitates problem solving using cartographic visualisation.

The Open GIS Consortium Inc (http://www.opengis.org) corporation consisting of more than 220 companies, government agencies and universities whose aim is to make spatial information and services more available and accessible to the broader community. As part of its objectives, the Consortium also encourages groups involved in the geospatial information industry, to submit discussion papers on specific topics relating to the development of spatial interface specifications.

In Australia, the Commonwealth Government has established the Australian Spatial Data Infrastructure (ASDI) which is a "national initiative to provide better access for all Australians to essential spatial data" (http://www.auslig.gov.au/asdi/). There are two organisations responsible for implementing ASDI, namely, the Australian and New Zealand Land Information Council (ANZLIC) and the Commonwealth Office of Spatial Data Management (OSDM). OSDM is primarily concerned with access and pricing regulations with respect to spatial data, whereas ANZLIC is responsible for coordinating the management of spatial data in Australia and New Zealand.

Some advisory groups have little understanding of Commonwealth objectives such as the ASDI, often giving low priority to projects that have a strong focus on making spatial data more readily available to farmers, decision makers and developers. Perhaps one reason for this lack of direction and understanding is due to concerns relating to licence conditions imposed by government custodians of spatial and non spatial data. Many believe that spatial and temporal data should be provided free of charge especially if data collection and analysis has been funded through the public purse.

The Spatial Information Industry Action Agenda (DISR, 2002) is a national policy framework to ensure maximum use and distribution of data products and services that have been publicly funded. The action agenda identified key problems relating to the distribution and access to spatial data.

These include:

- *Restrictions on the use of publicly funded data through the imposition of copyright and licence arrangements;*
- *The lack of "whole-of-government approach" to pricing and access to publicly funded data;*
- *Shortage of public funds to collect and maintain basic spatial information;*
- *A distinct lack of spatial data available on-line;*
- *A need to improve the efficiency of publicly funded data collection;*
- *Evidence that some government agencies have developed a monopoly on pricing structures.*

Making data more accessible is of paramount importance to the implementation of suitable land and resource management strategies.

Approximately 10% of the spatial data used in this project was available electronically. The remaining 90% were only available in hardcopy via land mail. The average time for the arrival of spatial data by land mail was around four months. Not surprisingly, water quality data were difficult to obtain electronically due to the lack of suitable file transfer protocol procedures. The current policy regarding data access for acid sulfate soils research is inadequate given the advances in computer technology over the last five years. Changes in thinking and attitude also need to be addressed and greater emphasis placed on awareness within Commonwealth and State Agencies with respect to the distribution and access to spatial data.

10.5.3 GIS for the Internet

Over the last five years developments in information technology revolution has seen the emergence of new Internet technologies; however cartographers have failed to capitalise on the unique benefits Internet technology can provide for the visualisation of map data (Richard, 1999). Although the Internet has influenced the development of new methods for capturing data in a GIS, at present there is no GIS web-based server system that can provide the functionality of a standard stand-alone GIS system such as Arcview or Arc/Info (Burrough and McDonnell, 1998). Most interactive GIS web sites offer maps containing overlays of specific spatial data such as roads, lakes and rivers but provide little information on the geographical features contained within the GIS and do not have the added functionality required for proper decision making.

There is an obvious need to develop an integrated system that will not only display typical geographical features in an on line or web-based GIS but can also provide additional functionality as a decision support system, with links to one or more database systems. This type of decision support system would provide the user with more detailed information relating to points or objects on a map together with the ability to query the data associated with the map objects, simply by using the map interface. The large costs involved in programming and in purchasing software licence agreements would preclude many organisations from being able to develop a system with the required degree of functionality expected from a decision support system.

The following discussion outlines the development of a low-cost Internet-based Geographic Decision Support System (GDSS) which uses a combination of readily available open source software linked to a MySQL (Structure Query Language) database system containing water quality results.

10.5.4 Web-Based GIS Software

There are only a handful of products available on the software market that provides varying degrees of web site interface functionality and support. The choice of software or combination of software systems depends on the level of functionality and sophistication required to perform specific tasks as well as the operating system requirements (i.e., Windows, LINUX and UNIX platforms). Cost considerations can also be a deciding factor.

A review of three current GIS web-based software was carried out to determine the most cost effective and efficient software available for the development of a Decision Support System (DSS) using a geographic interface. Ideally, it was important to look for an interface that could display a wide range of geographical files, such as those used in this thesis. An additional user requirement for the system was the ability to integrate disparate data form database systems such as Oracle or MySQL by using the geographic interface. All systems reviewed here achieved a basic level of functionality such as the ability to add or remove geographical layers and to use the "pan" or "zoom" functions normally found in stand alone GIS packages.

10.5.4.1 TNT Server™ Software

The TNT (Trusted Network Technologies) Server™ software is produced by MicroImages Inc, a US based company. The software has geospatial viewing and analysis tools and can support standard data formats such as ESRI shapefiles. The TNT server, which is loaded directly onto the web site server, publishes raster, vector, CAD, relational database, and other layers from a TNT Project file. The TNT Server costs around $US5,000 and the licence fees can vary depending on the platform requirements. This software has a suite of highly integrated applications, however it does not appear to have the ability to directly query external database systems via the map interface.

10.5.4.2 Arc/IMS Software

Arc/IMS is an Environmental Solutions Research International (ESRI) product that operates in a distributed environment consisting of clientside and serverside components, as shown in Figure 10.7. The Internet user requests information from the server. The request is then processed by the server which sends the information back to the Internet user. Both the client and the server communicate with each other using ArcXML. ArcXML is a GIS extension to standard extensible markup language (XML). XML files are similar to HTML pages, however the most important difference between the two is that ArcXML provides the mechanism for describing the content while HTML provides the process for displaying the web page structure for viewing. An attractive feature of Arc IMS is the simple but user friendly map interface (Figure 10.8) (ESRI, 2000).

ArcIMS has several disadvantages for both the client and the provider. Apart from the inability to support raster files, such as TIFF or GeoTIFF, the most notable disadvantage includes the high costs for technical support and the licence agreement ($US8,000). Perhaps, because of the commercial licensing arrangements, there is also a distinct lack of network support which is normally found amongst users of open source software. Unlike many other commercial and open source software, the server requirements for ArcIMS have very specific requirements.

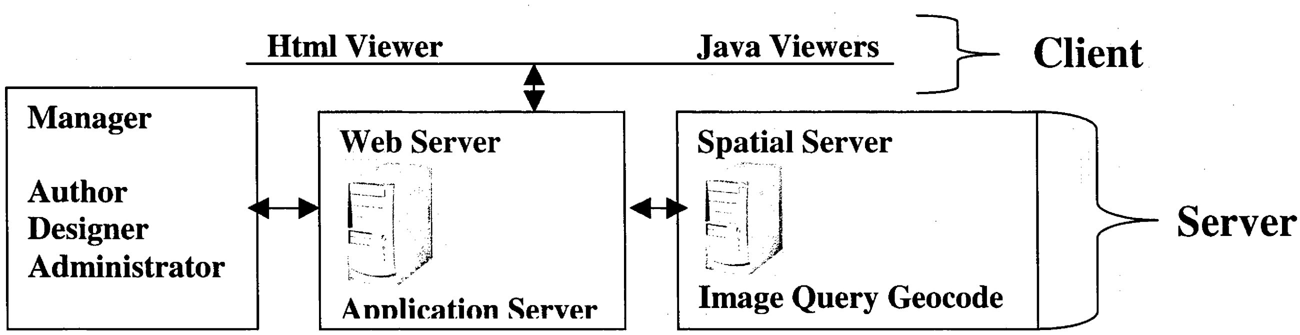


Figure 10.7 Client and server components for Arc/IMS (ESRI, 2002).

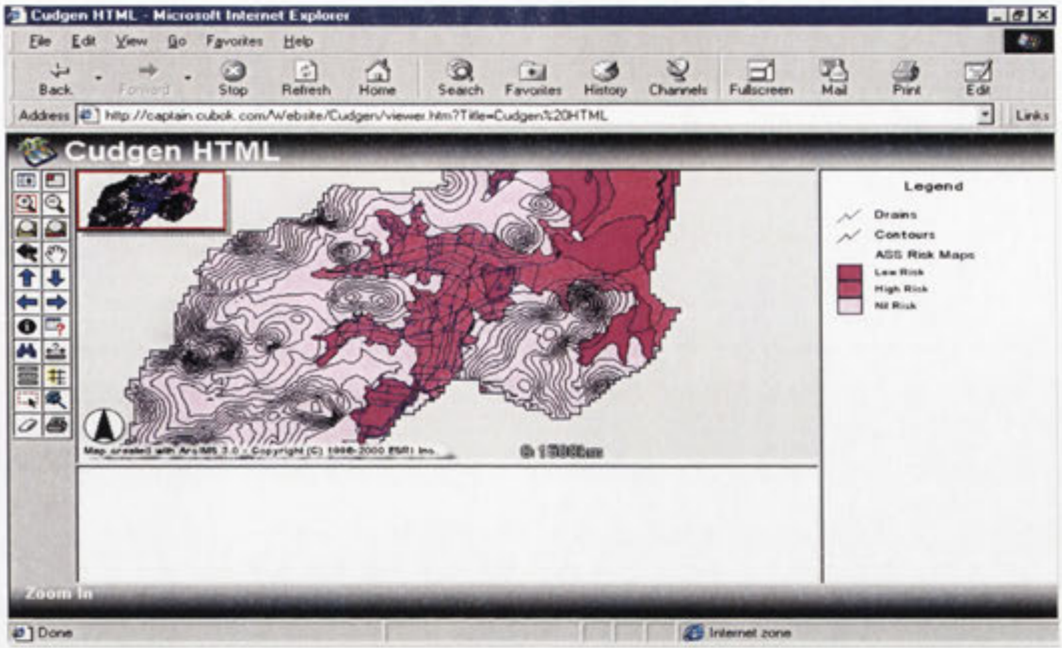


Figure 10.8 Arc/IMS User Interface.

10.5.4.3 MapInfo Extreme Software

The Map Info Extreme software package (produced by MapInfo Corporation Ltd) provides the user with the basic functionality discussed previously but in addition allows the user to query map data stored on a Microsoft SQL Server. This commercial software is ideally suited to the Microsoft Windows environment and has been developed specifically for users of MapInfo software.

10.5.4.4 Map Server Software

MapServer (http://mapserver.gis.umn.edu/) is a GIS web-based software used for displaying spatial information on the Internet. The software was originally developed by the University of Minnesota (UMN) in conjunction with the National Aeronautics and Space Administration (NASA) and the Minnesota Department of Natural Resources (MDNR). Several additional components were produced by the MNDNR and the Minnesota Land Management Information Centre (MLMIC). Unfortunately, MapSever does not have all the functionality of standard GIS package. However, despite this limitation, one unique advantage that MapServer has over other systems is the MapScript module. The MapScript module is unique to MapServer in that it provides an environment for developing specific applications that integrate disparate data from database systems such as Oracle, Sybase or MySQL. MapServer also has a PHP/MapScript module developed by DM Solutions (http://www.dmsolutions.on.ca/). This module is essential for transforming the data from a database system into web pages for viewing. PHP (hypertext preprocessor) (www.php.net) is a scripting language similar to HTML that allows the user to create dynamic webpages from the metadata. PHP-enabled web pages are similar to HTML pages. They can be created and edited in the same way as web pages are created using HTML. The Mapserver software provides navigational tools (zoom and pan) and query tools for providing information about the geodata used in the creation of spatial maps.

Unlike commercial web-based software systems, such as ArcIMS, MapServer software is classed as open source, with free access to an on-line group of network users that provide support to new and existing clients of Mapserver. MapServer (version 3.5) can operate on most UNIX systems and will run under Windows NT/98/95.

10.5.5 A Low Cost On-Line Geographic Decision Support System (GDSS) for Acid Sulfate Soils

The monitoring and reporting of water quality data is essential for the development of environmental protection programs and for ensuring that water quality standards are maintained. Data logging, as well as the statistical processes connected with data analysis, have been revolutionised in many areas of the natural sciences (Ripley, 1984). With an ever-increasing volume of field data that is now collected from coastal regions, there is a need to find a simple, reproducible method for the rapid display and visualisation of data. Since field data are often collected from a number of geographical locations it makes good sense to incorporate this type of data into a GIS for improved visualisation, analysis and decision support capabilities.

The McLeods Creek region of the Tweed Catchment is one of many sites along the coastal region of Australia where numerous research and management activities rely on the collection and monitoring of water and climate data. This site currently has several water quality stations and one weather station (Figure 10.9). Water quality results are collected from each station via telemetry to a central data logger. The results are then down loaded to a Microsoft® Access database system via telephone line. The system, however, lacked a process for automatically displaying the in-coming data or disseminating the results to cane farmers, researchers, state and local government officers. The Tweed Shire Council and researchers working at the McLeods Creek site recognised the need to develop an on-line system that could graphically display the input data in real-time.

Because of the clear requirement at this site and many others, a Geographic Decision Support System (GDSS) was developed that allowed researchers and other stakeholders to access an on-line database system of water quality data and to visually display the results through the use of a geographic interface. The GDSS is similar to a SDSS, however it does not support decision models as in the case of SDSS. For this reason, the term "Geographical" rather than "Spatial" was used to avoid confusion. The design and development of the GDSS for acid sulfate soils is consistent with the aims and objectives set down by the Australian Spatial Data Infrastructure (ASDI) and the Spatial Information Industry Action Agenda (DISR, 2002) discussed in section 10.5.2.

The GDSS used for the McLeods Creek Catchment was based on similar systems developed and designed in the United States of America. For example, the OrthoFinder site developed by the Wisconsin State Cartographer's Office (http://feature.geography.wisc.edu/sco/sco.html) uses the PHP/MapScript module of Mapserver to query a MySQL database containing a digitised orthophot catalogue for the Dane County. Other examples, similar to this one, are provided on the Mapserver website (http://mapserver.gis.umn.edu/gallery.html).

Several open source software components were used in the development of the GDSS. There are two main components that were used in the development of the GDSS. These include the Mapserver component and the MySQL database. The Mapserver component provides the "front-end" Geographic User Interface (GUI) and allows for the visualisation of geodata. Mapserver software was used as the map interface to the system because it can integrate with disparate database systems such as MySQL. MySQL was chosen because it has all the advantages of a relational (real-time) database in that it can handle queries from more than one user at the same time. This type of database system is also highly suitable because it is not only stable but is fast and easy to operate.

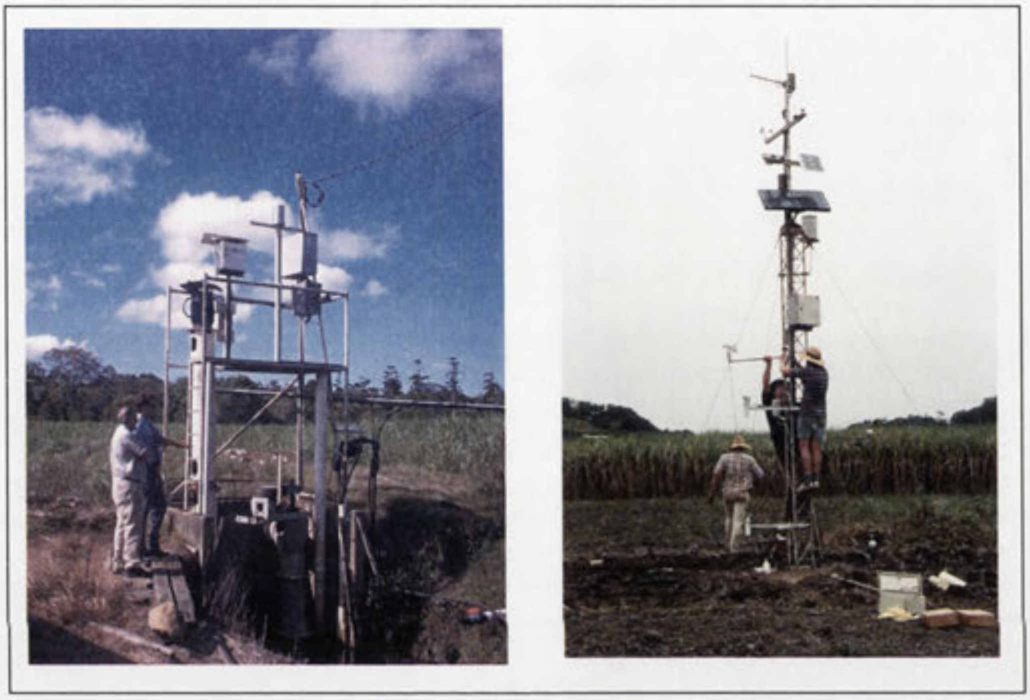


Figure 10.9 Water Quality monitoring station (left) and weather station (right) at McLeods Creek site.

Currently all the field results collected on the Tweed are stored on a Microsoft® Access database located on a personal computer. Since the Access database is not a web-based system, and is not compatible with Mapserver, it was necessary to transfer the data from the Access database to a MySQL database system.

The methodology used for setting up the server side components is available on the Mapserver web site (http://mapserver.gis.umn.edu/). For the purpose of this project, MapServer was installed on a LINUX platform (red hat version 7.2). The PHP/MapScript Module was used because of its compatibility with MySQL, which also uses PHP scripting language. The default vector file format, which MapServer uses, is the ESRI shapefile format. The system also supports raster files including

TIFF (Tagged Image File Format) and GeoTIFF files which allows the publication of aerial and satellite photographic images. The geodata files used in the construction of the Tweed MapServer system, included shapefiles of drainage maps, streamline data, risk map data, contour data, cane blocks and an aerial photograph of the McLeods Creek region (Figure 10.10). The software and hardware components of the GDSS are summarised in Table 10.1.

Table 10.1 Server Side components of the GDSS.

SERVER SIDE COMPONENTS	
Mapserver (PHP/Mapscript Module)	**MySQL (PHP API Module)**
▪ Geodata Files (shapefiles, Geotiff files, aerial photographs etc)	▪ Water Quality Data Files
▪ Mapfile	▪ Source Files (PHP Webpages)
▪ Source Files (PHP Webpages)	▪ Jp graph drawing library

The Mapserver component consists of the Geodata files while the mapfile or mapscript component uses a standard script to define the GIS data files to be used in the application and to display and query parameters. A MySQL PHP API (Application Programming Interface) module was used in the construction of the database. The PHP script was compiled as a module for an Apache web server. Real time data or archival data can be displayed in a graphical format using PHP and the graph drawing library for PHP "JpGraph". The JpGraph drawing library for PHP compiles a graph or image from the raw water quality monitoring data for viewing when the database is queried.

A series of shapefiles representing the geo-referenced monitoring stations were constructed in ArcView. These shapefiles were provided an identification number which was cross referenced to the data in the MySQL database. When a user queries the shapefile using the Geographic User Interface (GUI) it automatically displays the water quality data for that particular monitoring station. The user has the option of selecting and plotting several water quality parameters including pH, electrical conductivity, level, and temperature by date (Figure 10.10). The system can be adapted to suit a wide range of parameters and query demands.

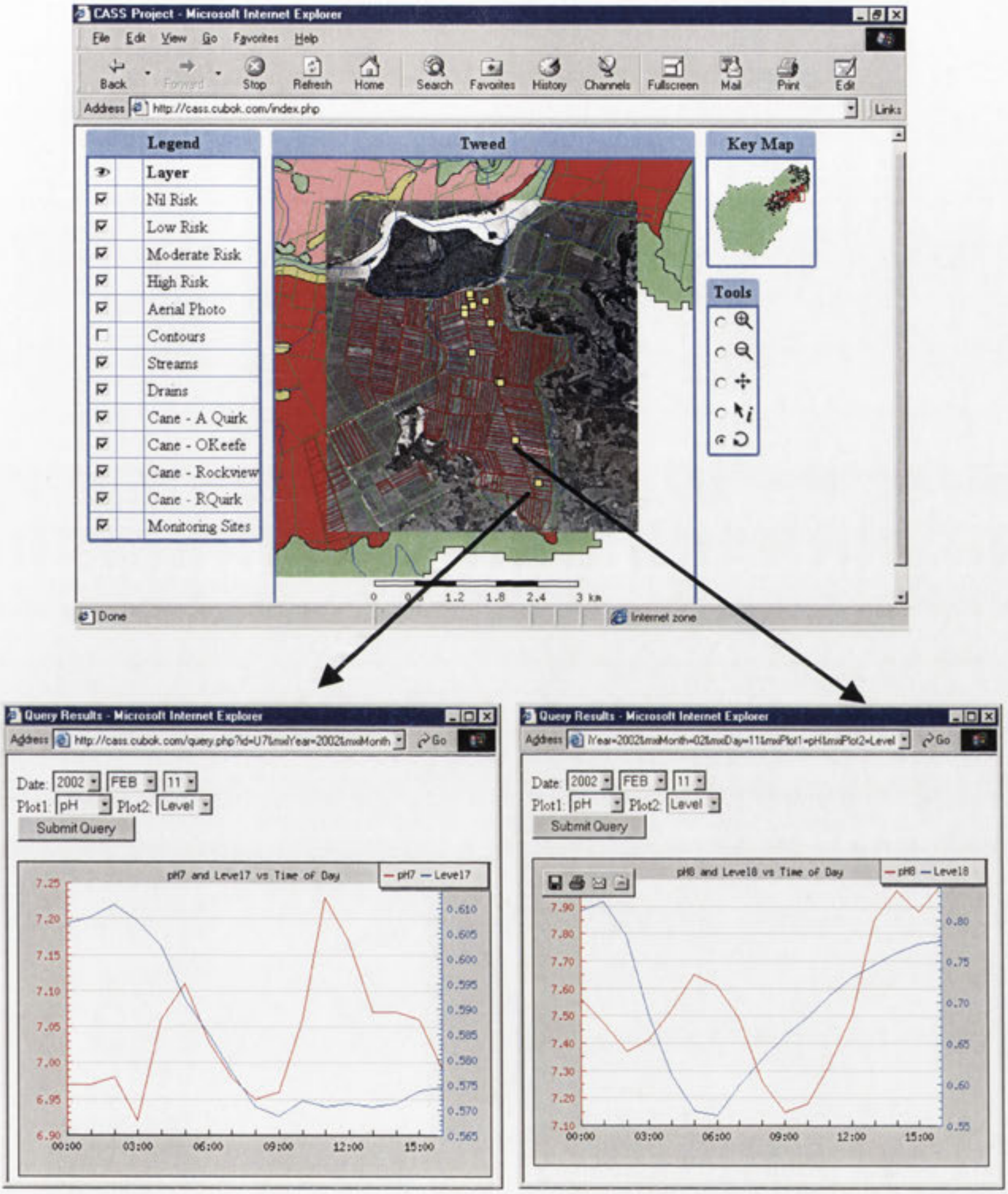


Figure 10.10 GDSS for the McLeods Creek region with an aerial photo overlay. Yellow boxes are the geo-referenced water quality monitoring stations.

Currently, the system does not allow for real-time data to be displayed or archived. This is because there is no process in place that can allow the transfer of data from the Access database to the MySQL database automatically. New data from the Access database system could potentially be automatically encrypted and transferred via File Transfer Protocol (FTP) method to the MySQL database located on a web server. SQL (Structured Query language) would then allow the user to interrogate the database and produce web pages from data stored in a MySQL database in real-time using PHP. Figure 10.11 supports how the process of transferring and encrypting data from an ACESS to a MySQL database could work.

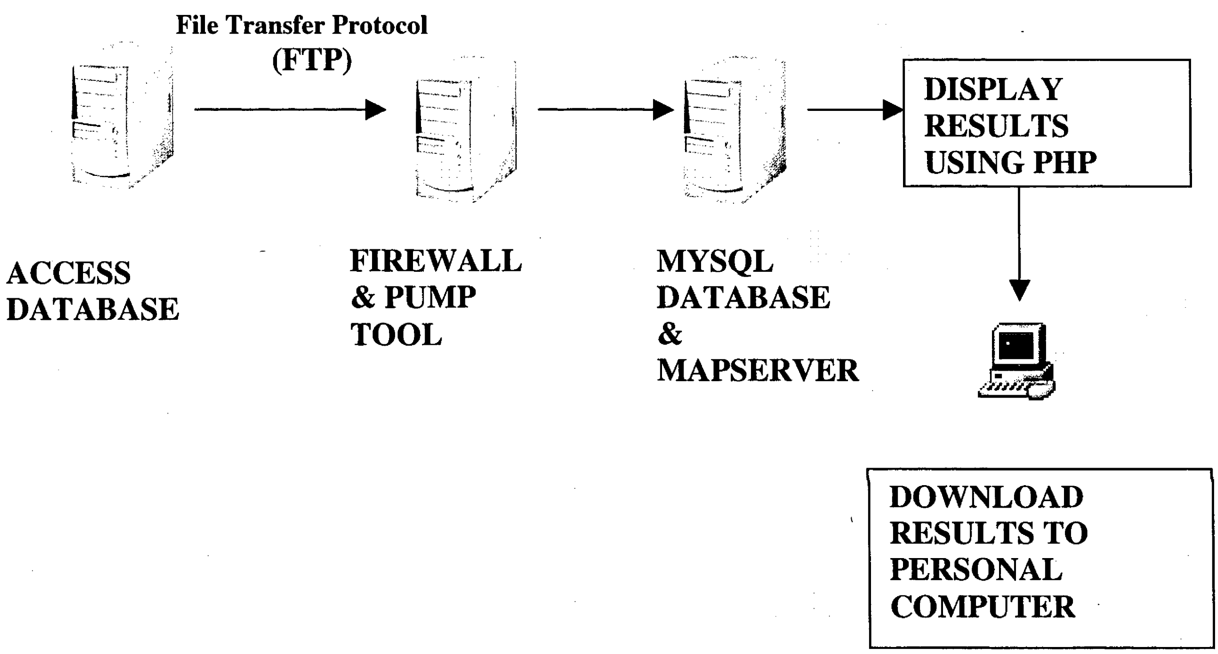


Figure 10.11 Sequence of steps for transferring and displaying data from an Access database to a MySQL database.

10.5.6 The Effectiveness of the GDSS as a Decision Support Tool for Environmental Managers.

The Geographic Decision Support System developed here (See: www.cassdirectory.org under the heading of "New Information" or at http://cass.cubok.com/) is a server based system aimed at providing relevant spatial and temporal information on-line and has been specifically designed to support decision making with respect to research activities, management and farming practices. Unlike a SDSS, the GDSS does not have the capability at this stage to support any sophisticated decision modelling functions nor provide any real interpretation of the water quality results. Any future GDSS development activities, should examine the possibility of developing decision models that can play an important role in predicting water quality and other environmental changes in response to climate and land management changes.

Despite the lack of decision modelling functions, the GDSS prototype developed for the McLeods Creek Catchment offers on-line access to data with vastly improved visualisation of both spatial and temporal data. The system can assist with statistical analysis and interpretation of data with respect to errors and anomalies within a short period of time and can be used as an effective, broad reaching communication system, for community and catchment management groups.

A small-scale feasibility study involving 60 individuals and organisations was carried out to assess the suitability of the GDSS across a wide range of organisations. The survey questionnaire was designed around three main categories. These included:

1. the type of organisation
2. location of the organisation
3. the usefulness of the GDSS to the organisation
4. major concerns or suggestions for additional functionality

The survey covered a range of different groups and organisations ranging from local government groups to research groups and private consultants. Not surprisingly, 80% of the groups surveyed believed that the GDSS would be useful to their organisation. Around 20% were not too sure whether a decision support system such as a GDSS could fulfil or complement their organisation's monitoring activities. Most of the groups surveyed were from research institutions.

The participants, who took part in the survey, raised some concerns. These included:

1. Quality of the metadata
2. Data integrity
3. Cost and maintenance issues

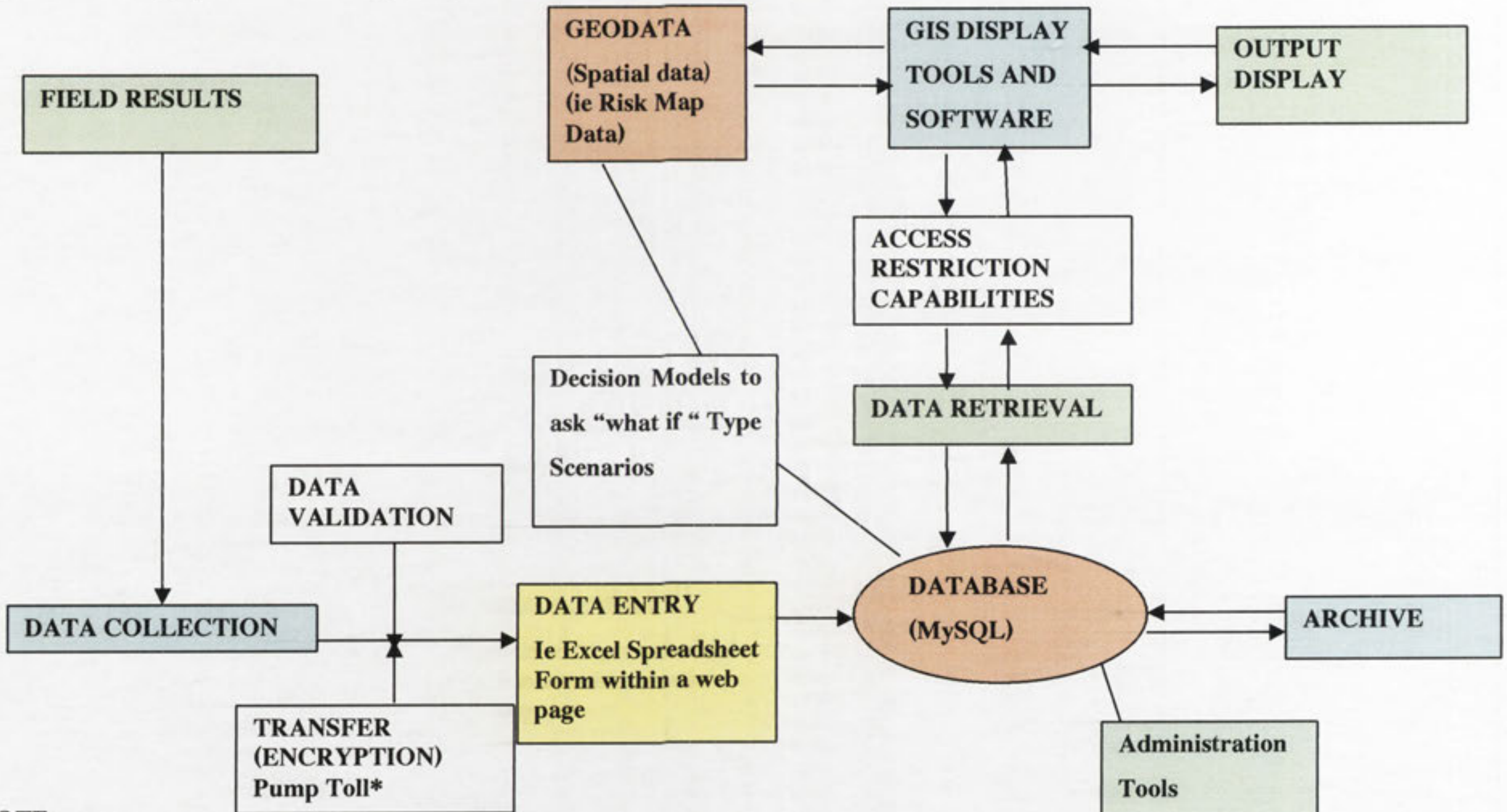
4. Ownership issues with respect to the data

Most groups surveyed had major concerns about the ownership of the data and how data integrity could be guaranteed and maintained. Many of the participants also talked about the quality of the metadata. The issue of providing suitable metadata for both spatial and temporal data must be considered as it is of fundamental importance for maintaining data integrity. The integration of the ECMS and the GDSS could provide an improved process for the inclusion of metadata through the introduction of improved knowledge based mapping and administration tools. As discussed previously, the ECMS provides a mechanism for the inclusion of metadata to a database system. It could also create an opportunity, through additional programming, for users to publish data, reports and other information relating to the site or catchment via the Geographic User Interface.

Clearly, these issues need to be taken into consideration in future development plans. Some of these problems such as ownership and authorised access to data, could be overcome through the introduction of improved security measures which would ensure that only authorised groups gain access to the system and its data. Figure 10.12 shows the overall structure of GDSS and the future components of the system.

Some of the concerns raised in the survey, particularly regarding proprietary rights, have existed long before the electronic information age. This suggests these issues are related to policy rather than problems specifically related to the technology. Monitoring programs should carefully identify the end users requirements and their needs, as well as the overall objectives of the monitoring program and the ownership of data.

Figure 10.12 Geographic Decision Support System (GDSS) and its Components.



NOTE:

***Pump Tool manages the selection of fields within the database and manages secure transfer of data .**
White boxes indicate future components.

10.6 Discussion and Summary

The need to effectively coordinate resource information is a crucial component in effective planning and management. The development of good catchment management practices is dependent on good communication and information strategies. In coastal areas, planners and policy makers will inevitably require better, cost-effective information and decision support systems, especially as the coastal zone continues to come under increasing environmental pressures from urban expansion. This chapter demonstrates how a cost-effective information and decision support system could be developed, using a combination of open source software components. The two systems discussed here have provided decision-makers with a sophisticated information and communication framework to assist in the development of sustainable environmental strategies for coastal catchments with acid sulfate soils. Both systems are ideally suited to organisations and groups that are limited in their ability to develop sophisticated information and decision support systems due to cost constraints.

The Electronic Content Management System (ECMS) provides a web portal that allows for the quick and easy retrieval of information. It is also a simple, non-technical approach to storing historic and current electronic information on acid sulfate soils and for the effective publishing, updating and archiving of information (such as scientific publications and reports).

Because of differences in metadata standards and the way agencies manage their data and information, it would be difficult to develop a truly integrated system of databases located throughout Australia. For electronic content information systems to work effectively there is a need for greater cooperation between government and non-government agencies with respect to information sharing. The Australian Government Locator Service (AGLS) Metadata Standard, developed for Commonwealth Government sites, is a good example of cooperation between government departments. However, there are difficulties associated with ensuring that all agencies follow the same standards regarding the quality and standardisation of metadata. Ideally, it is more effective in the long-term to develop a model similar to the "Meta node" approach (See: www.apec-vc.org) that could harmonise a host of database systems scattered throughout government and non-government agencies. The apec-vc.org web site unites the existing nodes (web sites) of three economies in the Asia-Pacific region into the one site or node. This site allows the user to search for information on environmental technologies across more than one economy.

The second system developed here is the Geographic Decision Support System (GDSS). The GDSS uses a combination of open source software programs designed specifically for the on-line visualisation of spatial and temporal data. The most important feature of the GDSS is the ability to provide more detailed information relating to specific points or objects on the map through the Geographic User Interface. The MapServer component of the GDSS is an important feature because of its ability to query disparate database systems such as MySQL through the Geographic User Interface. The development of the GDSS is consistent with the Australian Spatial Data Infrastructure (ASDI), in that it provides better access to spatial data.

The dissemination of data from monitoring programs to end-users is generally not considered in advance and in some cases it is not considered at all. Monitoring programs need to examine in more detail the process of data collection and visual display. It is essential that they avoid the "data rich-information poor" syndrome and address the overall objectives of the monitoring program. Clearly, much more work is needed in the area of developing on-line decision support systems.

The development of these two systems has highlighted some of the major issues relating to the management of temporal and spatial data. These include:

- the volume and diversity of information and data;
- the need to develop standardised methods for data and information collection, indexing and storage;
- the need to improve user interface mechanisms for improved access to information and data;
- the harmonisation and quality of meta data across agencies;
- the need for systems to distinguish between spatial and non-spatial data and
- data integrity.

CHAPTER 11
Final Discussion, Conclusion and Future Directions

Chapter 11. Final Discussion, Conclusions and Future Directions

11.1 Introduction

Coastal management in Australia and around the world is confronted by an array of complex issues that cut across the boundaries of the natural sciences, social and economic disciplines. There is a need for a systematic and integrated approach to the management of coastal catchments which not only takes into account the natural and socio-economic sciences but also recognises the fact that all the natural processes are connected and are never in a steady state but are spatially and temporally variable. Management strategies often fail to consider the broader implications of climate processes and the impacts of land management decisions. They seldom take into account the surrounding catchment hydrology and the inherent spatial and temporal variability of climate. As well, they often fail to consider the socio-economic implications associated with catchment and land use management decisions.

The purpose of this study was to develop a systematic approach to the management of coastal acid sulfate soils by examining the broader impacts of climate and land management decisions at the catchment scale. The study employed an integrated approach to the management and remediation of acid sulfate soils. This was achieved through the use of methodologies that are easily transferable and applicable to any catchment containing acid sulfate soils. Also, an integral component of this research involved the development of a Geographic Information System (GIS) for the management and remediation of coastal catchments with acid sulfate soils. The GIS incorporates a hydrological-water quality model to predict the magnitude of acid outflows events in response to climate and land management decisions. The model demonstrates the impacts agricultural drainage has had on the export of acid into aquatic ecosystems, such as Cudgen Lake and the Tweed River systems in northern NSW and was used to assess the impact of climate and land management changes on acidification in the Cudgen Catchment. The remediation and management options proposed for the Cudgen Catchment were assessed using the GIS hydrological-water quality model and considered their social and economic costs.

This work also identified and demonstrated how a cost-effective on-line Geographic Decision Support System can facilitate data management and provide land managers with a powerful and easily accessible decision-making tool aided by visualisation.

11.2 Inventory of the Main Findings

11.2.1 GIS-Hydrological Model for the Tweed and Cudgen Catchments.

This is the first time that a hydrological-water quality modelling approach, operating in a GIS environment, has been applied to the whole of the Tweed and Cudgen Catchments. Using the ANUDEM program, a 100 metre Digital Elevation Model (DEM) of the Tweed and Cudgen Catchments was constructed from spot height and stream line data. This accurate digital representation of the terrain facilitated the development of a rainfall-runoff model.

Monthly and annual runoff coefficients were determined for the Uki and Eungella Sub-catchments of the Tweed using spatially averaged rainfall and gauged streamflow data for similar periods. The modelling results provide a good approximation of the annual and monthly surface water flows for the Uki, Eungella and Tweed Catchments. There was a good correlation between the modelled and observed monthly mean flows for Uki and Eungella Sub-catchments (R^2=0.98, R^2 =0.97). Use of the ANUCLIM program and rainfall data from over four hundred stations, revealed that the monthly mean spatial rainfall was similar across all four catchments (Tweed, Uki, Eungella and Cudgen). Because of the absence of gauged streamflow stations, the determination of monthly and annual runoff coefficients was essential for estimating streamflow in the neighbouring Cudgen Catchment.

The acid sulfate risk map data was an integral component of the hydrological-water quality model and allowed for the estimation of acid surface water loads throughout the Tweed and Cudgen Catchments. The results showed that the total annual acid loads derived using the model are similar to the acid loads estimated by various researchers. The annual sulfuric acid water load for the Tweed River was estimated to be approximately 2,800 tonnes per year.

The model suggests that if the rate of acid evolution is constant over long periods, the dynamics of the system are controlled by the amount of water entering the system as runoff and leaving the system as evaporation. This is consistent with previous field interpretations which suggest that, apart from the intensity of a rainfall event, the position of the watertable and the available soil pore space, has a significant impact on water quality (Wilson *et al.,*1999). Therefore, two important characteristics of rainfall, namely the ratio of runoff to precipitation and its variability with respect to time and spatial characteristics, influence the export of acid and other materials into streams.

The analysis showed that topography and elevation could also influence rainfall distribution across the catchment. The distribution of rainfall across the Tweed Catchment was found to be strongly influenced by seasonal effects. Analysis of the spatial rainfall data, revealed that there was a noticeable seasonal variation in the spatial distribution in rainfall between the ocean-land fringe and the upper catchment. The long-term (last 100 years) and short-term (last 30 years) spatial rainfall results showed that, out of all three sub-catchments of the Tweed Catchment (ie Uki, Eungella and Cudgen), the Cudgen receives slightly higher rainfall during the winter months but slightly lower rainfall during the summer months. This difference was even more obvious when monthly spatial rainfall surfaces were generated for specific years. It was concluded that coastal catchments such as the Cudgen are more prone to seasonal variation in rainfall between the ocean-land fringe and the upper catchment due to their small size. This variation in catchment size can affect both the generation and transportation of acidic drainage. Changes in land use activities in the catchment can also influence the timing of acidification events. This early work prompted an investigation into the long-term climatic variability for the Tweed.

11.2.2 Trends in Rainfall Variability in the Tweed

Analysis of the catchment data revealed that changes in regional climate patterns are strongly influenced by large-scale climate systems such as El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) events. Although the PDO is a strong modulator of ENSO activity, its relationship to Tweed rainfall is weak and is, therefore, not a reliable forecaster of rainfall variability. The outcome of this research and from other studies (Power *et al.,* 1999a,b), showed that there was an association between the eastern Australian rainfall and the Southern Oscillation (SO), which operates on decadal time scales. However, this relationship is not as statistically significant as the association between SO and interannual time scales (Power *et al.,* 1999b). The results here showed that the best correlation between SOI and accumulated rainfall for the Tweed was for rainfall accumulation periods of around 84 months which corresponds to El Niño events occurring at intervals from 3 to 8 years. The ability to predict an El Niño event on a six year cycle is around 50% (R^2= 0.51). Rainfall in northern NSW was found to be significantly correlated with the SOI (R = 0.86, R^2 = 0.73) only when the PDO was negative. However, the methodology used in this analysis assumed that the SOI and rainfall are in phase.

The cycleplot analysis revealed a marked change in the seasonality of rainfall with conditions becoming notably drier for February, March, June and September. However, May was shown to be significantly wetter. A shift towards higher rainfall was also evident for October, November and December. These changes were identical for both short and long-term smoothing. It is interesting to note, that the shift towards drier conditions for February, March, June and September and an increase in rainfall for May, October and December was also reflected in the LAPGRD analysis of the short-term spatial rainfall. The change in seasonality occurred in the early 1980's. According to the cycleplot results for Tweed Heads, there was no change in the seasonal rainfall component for January, April, July and August. Murwillumbah revealed drier conditions for July with slightly higher rainfall for August. Drier conditions for February and March, coupled with wetter conditions for late autumn, favours both the formation of acid and acid products and their subsequent discharge into coastal streams. A late dry summer provides opportunistic conditions for increased acid production through watertable lowering and higher temperatures, while a month of heavy rainfall following a dry spell, provides a process for transporting acid and dissolved iron and aluminium to surface waters.

Paleoclimate studies have also shown that climate variability occurs on time-scales of hundreds to millions of years (Moy *et al.,* 2002). Current rainfall and climate data collected from weather stations, offers little insight into long-term climatic variability due to the short length of the record (i.e., ~100 years). More emphasis should be placed on the paleoclimate records as a means of providing better information on long-term climate variability. Sedimentation cores taken from coastal lakes, such as Cudgen Lake, may provide an excellent record of past climatic events – over time-scales as long as 10,000 years.

11.2.3 Rainfall Variability and Fish Kills

This work examined the pattern of significant fish kills events associated with acid sulfate soils in response to climatic variability. It was found that large-scale fish kills are closely linked to El Niño events. More specifically, the combination of an extremely dry climate followed by periods of intense rainfall result in acidic discharge and fish kill events. For all years in which a fish kill event was recorded, there was a distinct dry period in which rainfall percentiles were equal to, or below the 30 percent level.

The predicted timing of ecological disasters, such as fish kills, resulting from acidic discharge is challenging. Reliance on the use of large-scale climate systems to predict the timing of these kill events is highly problematic. With the short history of recorded fish kills in the Tweed, management of acid discharge events would benefit more from predictions based on monthly and annual rainfall. A simple soil water balance coupled with a probability tree model, based on monthly rainfall data, is an effective and simple process for predicting fish kill events.

Both the water balance study and the probability analysis revealed striking similarities between fish kill events. The water balance results showed that the height of the watertable and seasonal factors contribute to these events. Two fish kill probability trees were also constructed for predicting the precise timing of an event. The first probability tree model showed that, for a fish kill event to occur, the 12 monthly cumulative rainfall must not exceed 1698 mm. The second probability tree model used monthly rather than cumulative rainfall data to improve the sensitivity of the model predictions. The ability to predict a fish kill event can be determined quite simply from the amount of rainfall which takes places during the critical months, identified by the model. The model identified certain months of the year that are critical in determining the probability of a fish kill event. There is an 80% probability of a fish kill when monthly rainfall is low (<109 mm) on the 11^{th} and (<193 mm) 4^{th} month *before* the month of the event. There is heavy (> 258 mm) monthly rainfall during the month of the event.

It is important to recognise that the model developed here, for predicting fish kills takes into account the climate shift identified in the climate analysis. Extreme climate variation might take place in the future given global warming events and therefore any probability model would need to be constantly reviewed. Analysis and monitoring of large-scale climate patterns (ENSO and PDO cycles) would play an important role in this review process. Fish kill events are *not* an indicator or predictor of acid discharge. Other factors, such as the ability of fish to avoid acidic waters, dissolved oxygen levels and their breeding habits, also play an important role.

11.2.4 Remediation and Management Solutions for the Cudgen Catchment

This work has shown that there is a need for land management policies that support long-term water quality monitoring programs and allow for the implementation of improved land management practices which will accommodate the impacts of long-term climate variability.

The hydrological-water quality model was used to examine the effectiveness of long-term land management strategies on reducing acidification in Cudgen Lake. For the Cudgen Catchment, the concept of maintaining a high watertable as a management option is impractical due to the extreme climatic variability and existing land use rights. Furthermore, with a large existing store of acidity, sulfuric acid and acidic products will continue to leach out of the soil for many years after re-flooding. The strategies, which were considered for the Cudgen Catchment, included the removal of agricultural drains and the capping of selected regions of the lower floodplain. Other strategies, which were also investigated, were the reduction of surface water flow by intensive tree planting and the diversion of upland flows. The GIS hydrological-water quality model was used to determine the effectiveness of these strategies. The results established that two or more strategies are required to effectively reduce sulfuric acid loads by more than 12%.

The combination of drain reduction and capping can reduce acid surface water loads by as much as 32%. The process of capping involves the application of a surface load to sulfidic sediments. The weight of the capped material helps to consolidate soft sulfidic sediments through the de-watering process and raises the watertable above the oxidised sulfide material. In this thesis, the optimum thickness of the capping material was determined from previous investigations into the relationship between watertable depth and the consolidation of swelling soils. The optimum capping thickness was approximately 0.8 metres.

Capping of all acid sulfate soils in the catchment is simply not practical or economical and therefore priority should be given to areas that are most degraded such as scalded sites. Thus, accurate soil survey techniques are crucial in the determination of priority areas. Fortunately, for the Cudgen Catchment, major road construction works has also provided an effective long-term remediation solution, effectively capping 225 hectares or 28% of the acid sulfate soil Cudgen landscape, resulting in a 25% reduction in acid surface water loads to Cudgen Lake under current drainage conditions. Although these type of engineering projects often create divisions and conflicts between developers, land owners and environmentalists, they can provide some benefit in regions where acid sulfate soils are a major concern to water quality and where land is not intensively used. This was particularly the case for the Cudgen.

The hydrological-water quality modelling work also demonstrated the impact of different drainage density scenarios on the removal of acid surface water from the floodplain to the drainage network. The results showed that a 50% drainage density scenario was just as effective at removing sulfuric acid surface water from the floodplain as the current drainage network, suggesting that the current drainage system is excessive. However, a 75% reduction and the minimum, natural drainage density scenario was much less effective at removing acid surface water from the floodplain. Agricultural drains act as a conduit for the rapid transportation of surface water from the floodplain to the lake. A combination of a high watertable and a reduced drainage network would increase the risk of water logging and surface water retention as demonstrated in the modelling results. Under these conditions, surface water could remain confined to the floodplain for much longer periods. Clearly, drastic drain reduction strategies are not an effective remediation option unless measures are also taken to address the problem of surface water retention.

With respect to acid loads, it would appear that under a range of different drainage density scenarios, there is little change in the total annual sulfuric acid surface water loads entering Cudgen Lake. It would seem that a small, simplified drainage network (i.e., 25% drainage density) compensates for the inefficiency in removing acid from the floodplain by accumulating the water loads within the drainage network with greater efficiency. A simplified drainage structure would most likely translate into higher flow rates and increased fluxes. Normally, we would expect lower production rates from lower drainage densities as previous work has shown (White *et al.*, 1997). Therefore, the results obtained here could be a direct consequence of the model that assumes there is a fixed rate of acid production irrespective of the drainage density.

The results obtained here clearly reinforce the current belief that remediation strategies must be aimed at treating the problem at the drainage level in association with improved land management strategies. The removal of some agricultural drains should be carried out concurrently with laser levelling. This will ensure effective control of surface water runoff and reduce infiltration. Land managers, such as sugar cane farmers, should also ensure that the orientation of furrows is parallel to the direction of surface water runoff. The results of the detailed topographic survey revealed that simple changes in ploughing techniques could improve the efficiency of surface runoff and reduce surface water infiltration by as much as 36%.

Dredging has previously been undertaken, at various times, in some sections of Cudgen Creek to improve tidal exchange. However, this has proven to be ineffective in neutralising acid discharge from large outflow events. The adverse effects from the artificial opening of coastal lakes were outlined in the Healthy Rivers Commission Report (HRC, 2002) into coastal lakes. This report suggests that no further action should be taken to improve tidal exchange through dredging.

The work presented in this thesis showed that the re-routing of upland surface flows in combination with tree plantations, can reduce surface water flows, through the lower floodplain. The reduction in surface water flow that can be achieved from these strategies would result in small acid discharge events which can be managed using conventional lime dosing or allow for more effective neutralisation of acid by sea water in estuaries. Based on the modelling results, surface water flow could be reduced from 30,000ML/yr to 25,700 ML/yr if the forest cover of the catchment was increased from 52% to 87%. This represents a reduction in the runoff coefficient from 0.32 to 0.26. A combination of tree planting and the diversion of upland flows could reduce the acidified streamflow through the lower floodplain by as much as 62%. A reduction of this magnitude could improve the capacity of the estuarine water to neutralise the acid from small discharges. The water quality results presented in Chapter 5 suggest that the buffering capacity of the sea water can effectively neutralise the acid from small discharge events.

11.2.5 Cost of Remediation and Ecosystem Services for the Cudgen Catchment

Natural ecosystems, such as in the Cudgen Catchment, are generally not recognised as having a commercial or economic value when compared to the goods or services produced in the catchment - yet they are essential for the future of man-kind. According to the Costanza *et al.* (1998) model, the total value from ecosystems services for the Cudgen Catchment is $US11 million per year or around $AUD20 million dollars per year (based on an exchange rate of 55 cents). The cost of some remediation strategies, such as capping, is simply too expensive for many catchment management groups or individual land holders. For example, to cap 34% of the lower Cudgen floodplain it would cost between $AUD6 and $AUD22 million dollars, depending on where the capping material is sourced. However, many of the remediation options discussed in this thesis are relatively inexpensive when balanced against the benefits derived from ecosystem services. The cost of in-filling of individual drains varies from $AUD200 to $AUD58,000 per drain, depending on the level of treatment and the dimensions of each drain. A 50 percent reduction in drainage density in the Cudgen floodplain could cost as much as $AUD855,000. The costs of these strategies, however, represent a small price to pay for long-term environmental sustainability.

The application of some remediation strategies depend on a number of factors including existing land use activities as well as the willingness of individual stakeholders to adopt changes in management techniques. For the Cudgen Catchment, acid sulfate soil management must address the underlying socio-economic problems that may cause some land holders to resist change. There may be a need for some industries, such as grazing, to shift to enterprises that provide environmental and economical sustainability.

Tree planting, for example, provides potential income from timber plantations and may therefore be a "win-win" situation for both the environment and land holder. Tree farming for carbon sequestration and timber in the Cudgen Catchment can provide farmers with a Net Present Value (NPV) of around $AUD1 million per year or $AUD32,000,000 for each of two harvests over a 60 year period. This assumes a discount rate of 7% and 3,000 hectares of an extremely fast growing, intensively managed eucalypt plantation. This result is largely determined by the choice of discount rate. A discount rate of 5% provides a better return from forest plantations regardless of the type of tree model used. This work also revealed that the gross margin per hectare from timber production ($AUD340) is higher than for beef or dairy farming ($AUD90) making timber production an alternative enterprise for farmers.

The successful management of these coastal catchments requires the resolution of existing conflicts between, land and estuarine users, government regulators and community groups. Therefore, it is essential that the development and planning processes should involve community and stakeholder participation. Effective communication and dialogue between all groups involved in the process is an essential factor in achieving the shared outcomes.

11.2.6 Improved Communication Strategies for Better Management of Acid Sulfate Soils

Woodhead (1999) noted that, the lack of effective communication strategies has led to "sensationalism of misinformation" by media groups resulting in considerable "polarisation in opinions" and ideas between community groups and stakeholders. A majority of respondents in her survey identified a need for a more formal education and communication forum aimed at all social groups, from school children through to hobby farmers. To improve the flow of reliable information between stakeholders, community groups and organisations, the "National Strategy for Acid Sulfate Soils" aimed to establish a "framework for national communication" through the establishment of a web site (NWPASS, 1999). Unfortunately, the National Strategy provided no mechanism for the development of a national communication network that could deliver reliable information exchange between various organisations and agencies.

In an attempt to address these issues, two communication systems were used to demonstrate the effective use of information and communication technology (ICT) in acid sulfate soil management, thus providing a framework for improved communication and information dissemination at the national level. These included the Electronic Content Management System (ECMS) and the Geographic Decision Support System (GDSS). The implementation of the ECMS (www.cassdirectory.org) required the establishment of a standardised classification system. This provides a basis for the creation of suitable metadata that will allow for the classification and indexing of new and existing electronic information. Further, it also permits the rapid retrieval of information through improved search function capabilities, thereby allowing searches for particular documents using more than one parameter (ie. author, subject, description or date). However, it is important that efforts are also made to establish a more standardised metadata structure for the ECMS based on the

Australian Government Locator Service (AGLS) metadata standard developed for commonwealth government sites. This will increase the existing functionality of the ECMS developed here through improved compatibility with existing government sites.

The GDSS was developed primarily for researchers and cane farmers as an on-line decision support tool, with a strong dependence on the automatic graphical display of water quality data through a Geographic User Interface (GUI). Good visualisation of raw or archival data can assist land managers in decision making (Tufte, 1983). The development of the GDSS is consistent with the Australian Spatial Data Infrastructure (ASDI), in that it provides better access to spatial data. Since both communication systems were developed using open source software, they provide a low cost alternative to developing a reliable framework for effective communication and information transfer between organisations and agencies.

11.2.7 Brief Synopsis of Results

The climatic change in rainfall seasonality that occurred in eastern Australia since the early 1980s, means that we can expect acidification events to continue to occur in northern NSW for some time to come. The future management of acid sulfate soil catchments require a systematic approach, that integrates the natural, as well as the socio-economic factors and land management changes. It must treat all the processes within coastal catchments as an integrated system. From work presented in this thesis, the development of an integrated approach to the management of coastal catchments with acid sulfate soils is dependent on:

1. Climate and climatic variability, including long-term climate change.
2. The availability of hydrological and climate modelling programs that will improve the understanding of current and past catchment system dynamics such as ground and surface water flow.
3. The economic value of ecosystem services balanced against the cost of remediation to prevent further environmental degradation.
4. The social and economic costs to communities.

5. Stakeholder's willingness to embrace change for the long-term benefits.
6. Effective use of communication and data presentation through improved visualisation techniques, including better methods for accessing all forms of data sets, including spatial and non-spatial data.
7. Implementation of land management strategies in consultation with community groups and stakeholders.
8. Better integration of on-ground works with monitoring programs.

These functions are represented diagrammatically in Figure 11.1. The cycle of events and processes relating to integrated catchment management of ASS is analogous to the DPSIR model shown in Figure 1.2 (Chapter 1).

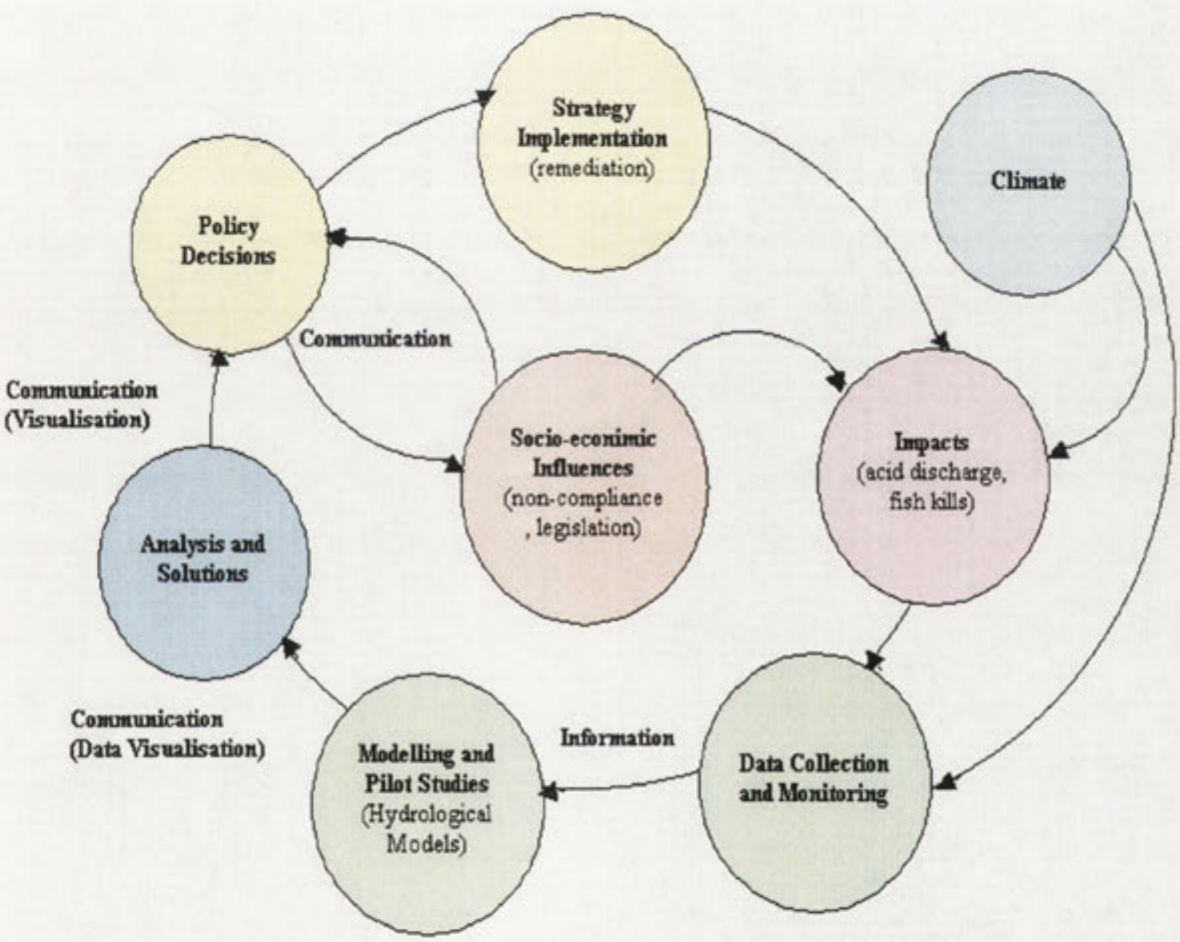


Figure 11.1 Cycle of events and processes associated with acid sulfate soils remediation and management.

11.3 Future Directions

11.3.1 Future Application and Improvements in the Methodology

The hydrological-water quality model developed here is flexible enough to allow for alterations to the input data, such as changes to the runoff coefficient and acid land loads. The model offers land management groups a tool for assessing the impact of drainage and climate on the transportation of acid and acid products. Remediation options can be put into place to lessen the degree of acid runoff based on model predictions. More importantly, it will allow land managers and other stakeholders to prioritise their management options and set long-term management plans. The model could also be used to set realistic acid discharge targets in response to land use changes and climate variability.

However, to realise the full potential of an integrated GIS hydrological-water quality model, it is necessary to develop a real time dependent system that can track and display the spatial movement and distribution of hydrological events in real-time. A system with this degree of functionality will need to rely on an effective relational database structure coupled to sophisticated modellings programs. The development of the GDSS is a first step towards an on-line spatial decision support system that could ultimately fulfil these capabilities. Furthermore, the integration of a modelling component to the GDSS would ensure that users have better access to modelling outcomes through an easily accessible graphic user interface.

Despite the power of modern day computers and computer programs, the ability to accurately model and predict events that occur in the real world is a challenge. This is because the operational requirements of these models are largely dependent on the quality of information and data provided by field operations. This is especially the case for climate, which has a very large influence on the processes that affect land degradation and water quality. It is very difficult to accurately model changes to the land and its response to changes in climatic events, if there is a lack of quality data. Fortunately, for this study, access to climate data was not a problem, however, there was a lack of reliable spatial data relating to the distribution of ASS with respect to concentration and land loads. Unfortunately, many decision-making authorities do not place enough emphasis on monitoring, preferring to initiate on-ground activities without carefully considering the consequences of such actions through proper prediction and monitoring programs. Such actions are often classed as adaptive management. However, adaptive management assumes that mistakes can be easily reversed. Harris (1999) suggests that estuaries may be hysteretic so that mistakes cannot be easily reversed. This appears to be the case with acid sulfate soils. According to Wilson (1995), the proper management of these soils will ultimately rely on better methods of assessing the distribution and concentration of sulfides due to the large quantities of pyrite present in these soils.

The distinction between PASS and AASS has often relied on the degree of soil ripeness as well as the presence of jarosite (Burrough *et al.*, 1988) clearly identified by its yellow colour. However, some authors have reported the presence of AASS in some acid sulfate soil landscapes even though jarosite was absent from these soils (van Mensvoort and Le Quang tri, 1988; Wilson, 1995). The reliance on pH to determine the extent of pyrite oxidation can also be misleading and inaccurate as a considerable quantities of unoxidised pyrite can be found in regions where the pH of the soil is below 6.0 (Wilson, 1995).

It is not unreasonable to suggest that the rate of pyrite oxidation may vary depending on the extent of land-use activities in conjunction with fluctuations in watertable levels. A low watertable in association with high temperatures provides ideal conditions for pyrite oxidation as well as increased potential for soil ripening (van Breeman, 1973b; Dent, 1986) and permeability (White *et al.,* 1997). The extent of these physical changes will determine the rate of pyrite oxidation down the soil profile. In addition, in many acid sulfate soil environments, there are large stores of acidity already in the soil that can be exported by drainage.

Clearly, the accuracy of the hydrological-water quality model developed in this study will depend on better methods of accurately identifying the spatial distribution of acidity across landscapes, as well as the rate of acid export under a range of different land use and climatic scenarios. However, there are many questions that remain unanswered. To what extent can acid export be attributed to changes in land use activities? Are there certain conditions that favour the oxidation of pyrite than others, such as the application of agricultural fertilisers?

Secondly, the model will require modification to deal with watertable fluctuations as well as methods to model the impact of tidal exchange and buffering capacity on acid discharge originating from low surface flow events. Modelling programs such as DRAINMOD (Skaggs, 1980) can predict the impacts of drainage and other associated surface water management strategies on watertable dynamics. A combination of both the hydrological-water quality model developed here and DRAINMOD could provide a much more powerful analytical tool for simulating low flow acid discharge events. Thirdly, there is also a need to develop a more effective method of model calibration to suit a range of different climate and land use activities. This will of course depend on the development of improved methods of identification and distribution of acidity across different landscapes.

Finally, to examine the impact of new drainage structures on flow conveyance through the lower Cudgen floodplain, it may be necessary to improve the sensitivity of the model by developing a new DEM with finer spatial resolutions, coupled with integrated drainage network modelling systems such as IDNAS (Integrated Drainage Network Analysis System) (Yang *et al.*,1999). Systems such as DRAINMOD and IDNAS are suitable for simulating flow events over small areas, however, newer versions of DRAINMOD can simulate watertable dynamics at the catchment scale (Fernandez *et al.*,2001).

11.3.2 The Necessity for More Complex Modelling of Acid Sulfate Soils

Land use and climatic influences also have major implications on the formation and mobilisation of acid products such as dissolved iron and aluminium. These factors also affect the complex chemical interactions that take place between the soil and atmospheric environments. Recent research has shown that the flux of sulfur dioxide from sugar cane fields is closely linked to soil water evaporation (Macdonald *et al.*, 2004). Because sulfur dioxide has high water solubility there would appear to be a direct link between soil water evaporation and the evolution of sulfur dioxide from acid sulfate soils landscapes. This strongly suggests, that the evolution of gases from the soil to the atmosphere are controlled by environmental factors such as rainfall and evaporation. Clearly, the long-term impacts of climate change and seasonality changes on sulfur, iron and nitrogen cycles within acid sulfate soils, requires further investigation.

Further field studies should identify and quantify the associations between sulfur, nitrogen, iron and carbon, in both drained and undrained acid sulfate soil landscapes and under different land management regimes. A better understanding of these processes may involve atmospheric measurements, analysis of microbial activity and soil measurements, in association with some surface and groundwater modelling.

Future work should also examine the transportation and effects of other dissolved species, including aluminium and iron. The long-term impacts of these constituents on the environment, especially with respect to the health of human and marine organisms, are still largely unknown. The hydrological-water quality model could also be used to model the concentrations of these constituents.

11.4 Final Comment

We are only just beginning to understand the complex nature of acid sulfate soils and the environmental, economic and social impacts these soils have on the coastal zone. The knowledge gained from years of investigation into these soils has been used in conjunction with modelling programs to determine the current and long-term impacts of anthropogenic and climatic factors on acid discharge from coastal floodplains. It is expected that these modelling and communication tools will prove to be more relevant to the management of acid sulfate soils, particularly as more is discovered about the complexities of climate and the changes relating to the physical and chemical interactions which takes place in these soils. Finally, because the coastal zone is a heterogenous system that is in a continuous state of change, it is important to adopt an integrated approach to the management of these coastal catchments.

"The significant problems we face cannot be solved at the same level of thinking we were at when we created them."

Albert Einstein.

References

Aaso,T.(1996).A Methodology for Mapping Drains on Coastal Floodplains. UNSW Unpublished report, DLWC Kempsey.

Aaso,T.(2000). Towards Sustainable Landuse within Acid Sulfate Soil Landscapes. A Case Study on the Maria River, New South Wales Australia. Unpublished Masters Thesis, Lund University, Sweden.

ABARE .(2002). Important Competitiveness of Australian Aquaculture. Eds Love, G and Langenkamp D. *A report for the Fisheries Resource Research Fund*, Canberra, July.

ABS .(2000). *Year Book Australia, Forestry, Fishing and Aquaculture (Catalogue No 1301.0)* Australian Bureau of Statistics, Canberra.

ABS .(2002). *Australian Farming in Brief* (Catalogue No 7106.0) Australian Bureau of Statistics, Canberra.

ABS .(1996). *Census of Population and Housing: Population Growth and Distribution, Australia*, 1996 (Cat. No.2035.0) Australian Bureau of Statistics, Canberra.

Ahern, C.R., Ahern, M.R and Powell, B.(1998). *Guidelines for Sampling and Analysis of Lowland Acid Sulfate Soils (ASS) in Queensland.* QASSIT, Department of Natural Resources, Resources Sciences Centre, Indooroopilly, Queensland.

Allen, R.G., Pereira, L.S., Raes, D and Smith, M.(1998). Crop evapotranspiration – *Guidelines for computing crop water requirements – FAO Irrigation and Drainage Paper 56.* Food and Agriculture Organisation. Rome

Alley, W.F. (1984). The Palmer Drought Severity Index: Limitations and assumptions. *Journal of Climate & Applied Climatology* 23: 1100-1109.

Andrienko, N and Andrienko, G. (2001). Intelligent Support for Geographic Data Analysis and Decision Making in the Web. *Journal of Geographic Information and Decision Analysis*, Vol 5, No 2, pp 115-128.

Anon .(1992). *Australian Water Quality Guidelines for Fresh and Marine Waters* (Australian and New Zealand Environment and Conservation Council: Canberra).

ANU Forestry .(2000). Market Report. Carbon Credit Markets. On-line report http://www.farmwide.com.au/features/report12.pdf

ANZECC .(1992). *Australian water quality guidelines for freshwater and marine waters,* Australian and New Zealand Environment and Conservation Council. *National Water Quality Management Strategy, Australia.*

ANZECC/NHMRC .(1992). *The Australian and New Zealand Guidelines for the Assessment and Management of Contaminated Sites.* The Australian and New Zealand Environment and Conservation Council (ANZECC) and National Health and Medical Research Council (NHMRC) Publication, Canberra.

Asafu-Adjaye, J.(2000). *Environmental Economics for Non-Economists.* World Scientific Publishing. Singapore. ISBN 981-02-4013-9.

ASSMAC.(1996). *Acid Sulfate Soils Analytical Methods.* Acid Sulfate Soils information and awareness publication.

ASSMAC .(1999a). *Financial Assistance Options to improve Acid Sulfate Soil Management and Improve Quality of Drainage Water.* Discussion paper prepared by ASSMAC for Water CEOs.

ASSMAC .(1999b). *Remediation of Acid Sulfate Soils in New South Wales.* Report prepared by the NSW Acid Sulfate Soil Management Advisory Committee.

Atkinson, G., Aaso, T., Hallinan, M., Franklin, J., Kemsley, R., Rea, S and Johnstone, P .(2000). *Acid Sulfate Soils Drainage Network Mapping, Northern NSW.* DLWC Sydney.

AUSLIG .(1992). GEODATA TOPO-250K *User Guide*. Australian Survey and Land Information Group, Canberra.

Auxtero, E.A and Shamshuddin, J.(1991). Growth of oil palm (Elaesis guineesis) seedlings on on acid sulphate soils as affected by water regime and aluminium. *Plant and Soil*, 137: 243-257

Ayres, R. U .(1998). Comment: The price-value paradox. *Ecological Economics* 25, pp 17-19.

Barbier, E.B .(1994). *Valuing Environmental Functions: Tropical Wetlands*. Beijer reprint series No 26. Beijer International Institute of Ecological Economics. Royal Swedish Academy of Science. Sweden.

Bagri, A., Blochhus, J and Vorhies, F .(1998). *Economic Values of Protected Areas: A Guide for Policy Makers and Park Managers* . Draft 2. Gland, Switzerland: IUCN, World Commission on Protected Areas.

Barthel, K.G., Barth, H., Murray, C.N., Suranyi, M and Dubois, K .(1999). *European Land-Ocean Interaction Studies Implementation Report, Ecosystems Research Report 33*, On-line report: http://europa.eu.int/comm/research/eloise/eloise-ph2.pdf

Beasely, D.B and Huggins, L.F .(1982). *ANSWERS users manual. EPA* –9105/982-001. US EPA, Chicargo, IL.

Beer, I.B .(1992). The Distribution of Acid Sulphate Soils in the Lower Cudgen Lake Catchment, NSW. Unpublished Honours Thesis, School of Geography, University of New South Wales.

Becker, R., Chambers, J and Wilks, A .(1988) *The New S Language, A Programming Environment for Data Analysis and Graphics*. Wadsworth and Brooks/Cole.

Berner, R.A .(1978). Sulfate reduction and the rate of deposition of marine sediments: Earth Planet. *Science Letters*, Vol. 37, pp.492-498

Berner, R.A .(1972). Sulfate reduction, pyrite formation, and the oceanic sulfur budget. P 347-361. In: D.Dyrssen and D.Jagner (eds*), The Changing Chemistry of the Oceans.* Nobel Symposium No20. Wiley, London.

Berner, R.A., Baldwin, T and Holdren, G.R .(1979). Authigenic iron sulfides as paleosalinity indicators. *Journal of Sedimentary Petrology*, 49:1345-1350.

Berner, R.A .(1984). Sedimentary pyrite formation: an update. *Geochimica Cosmochimica Acta* 48: 605-615

Binley, A and Beven, K .(1992). Three-dimensional modelling of hillslope hydrology, *Hydrological Processes* 6; 347-359.

Bjerknes, J.(1966). A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus,* 18, 820-828.

Bloomfield, C and Coulter, J.K.(1973). Genesis and management of acid sulphate soils. *Advances in Agronomy*, 25: 265-326.

Bloschl, G and Sivaplan, M.(1995).Scale issues in hydrological modeling: A review. *Hydrological Processes* 9: 313-330.

Bolton, K.G.E., Sullivan, L.A, Rosicky, M.A., Ward, N.J., Balson, A and Bruce, J.J .(2002). Changes in water and soil chemistry in response to effluent irrigation in a peat acid sulfate soil. *Proceedings of the 5th International Acid Sulfate Soils Conference*, Tweed Heads, NSW Australia, August 25-30 th.

Bonjer, D .(1991). Catchment Management Issues in the Cudgen Catchment, NSW. *Integrated Project Report*, UNE Northern Rivers.

Bosch, J.M and Hewlett, A .(1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*. 55, 3-23.

Boston, T and Stockwell, D .(1994). Interactive species distribution reporting mapping, and modelling using the World Wide Web. *Second International WWW Conference 1994*: Mosaic and the Web-Chicago, USA.

Bouwer , H .(1974). Developing drainage design criteria. In: *Drainage for Agriculture*, Van Schilfgaarde, J. (ed). American Society for Agronomy, Inc., Madison, Wisconsin pp 66-81.

Brown, T.E., Morley, A.W., Sanderson, N.T and Tait, R.D.(1983). Report of a large fish kill resulting from natural acid water conditions in Australia. *Journal of Fish Biology* 22, pp 335-350.

Bronswijk, J.J.B and Groenenberg, J.E.(1993). A simulation model for acid sulphate soils, 1: basic principles. In:D.L.Dent and M.E.F.van Mesnsvoort(eds.). *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils* pp.341-356. International Institute for Land Reclamation and Improvement: No53: Wageningen.

Bryant, E.(1997). *Climate Process and Change*. Cambridge University Press. UK p 5.

Brutsaert, W.H.(1982). *Evaportation into the Atmosphere. Theory, History and Applications*. D. Reidel Publishing Co., Dordrecht, Holland.

Bureau of Meteorology.(1988). *Climatic Averages of Australia*. Commonwealth of Australia, Australian Government Publishing Service, Canberra.

Bureau of Meteorology .(2003a). *Climatic Averages of Australia*. Commonwealth of Australia. On-line publication: http://www.bom.gov.au/cgi-bin/climate/cgi_bin_scripts/annual_rnfall.cgi

Bureau of Meteorology.(2003b). Commonwealth of Australia, *On line publication*: http://www.bom.gov.au/lam/climate/levelthree/c20thc/cyclone3.htm

Burgess, V.(2002). Closing gaps between scientists, policy-makers. *Canberra Times*, June 15, pB1.

Burrough, P.A., van Mensvoort, M.E.F and Bos, J.(1988). Spatial analysis as a reconnaissance survey technique: an example from acid sulphate soils regions of the Mekong delta. In: H Dost (ed) *Selected papers of the Dakar symposium* *on acid sulphate soils*, pp 68-89. International Institute for Land Reclamation and Improvement Publication No 44, Wageningen.

Burrough, P.A and McDonnell,R.A.(1998). *Principles of Geographical Information Systems, Spatial Information Systems and Geostatistics.* Oxford University Press.

Burroughs, W.J.(1997). *Does the Weather Really Matter? The social implications of climate change.* Cambridge University Press. Cambridge.

Callinan, R.B., Fraser, G.C and Melville, M.D.(1993). Seasonally recurrent fish mortalities and ulcerative disease outbreaks associated with acid sulphate soils in Australian estuaries. In: D.L.Dent and M.E.F.van Mesnsvoort (eds.). *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils* pp.403-410. International Institute for Land Reclamation and Improvement. Publication No. 53, Wageningen.

Casner, S.M.(1991). A Task-analytic Approach to the Automated Design of Graphic Presentations. *ACM Transactions on Graphics.* 10, 11-151.

Cayan, D.R.(1996). Interannual Climate Variability and Snowpack in the Western United States, *Journal of Climatology*, 9, 928-948 Chambers, J.M and Hastie, T. (1992). Statistical models, In S, Wadsworth and Brooks/Cole. Pacific Grove, California.

Chambers, J.M and Hastie, T.J.(1992) *Statistical Models,* in Chambers, J.M and Hastie, T.J (eds), Wadsworth & Brooks/Cole, Pacific Grove, California.

Cheers, B.(1992). The effects of runoff from acid sulfate soils on the aquatic environment: A survey of benthos in Cudgen Lake and Creek, Northern NSW. *Report prepared as part of an integrated project for the Faculty of Resource Science and Management*, University of New England, Northern Rivers.

Christie, D., Spencer, L., Senthliselvan, A.(1992). Air quality and respiratory disease in Newcastle, New South Wales. *Medical Journal of Australia* 156: 841-3

Clarke, K.C., Parks, B.O and Crane, M.P.(2001). Spatial Decision Support Systems and Environmental Modeling: An Application Approach. In: *Geographic Information Systems*. Prentice Hall, ISBN 0-13-040817-4, p52.

Clear Solutions Newsletter.(2002). *An on-line publication. Earth Systems Pty Ltd,* June 2002. http://www.earthsystems.com.au/downloads/Clear%20Solutions%20June'02.pdf

Cleveland, W.S and Devlin, S.J.(1988). Locally-Weighted Regression: An Approach to Regression Analysis by Local Fitting. *Journal of the American Statistics Association*, 83,pp 596-610.

Cleveland, W.S., Devlin, S.J and Grosse, E.(1988). Regression by Local Fitting: Methods, Properties and Computational Algorithms. *Journal of Econometrics,* 37, pp 87-114.

Cleveland, W.S and Grosse, E.(1990). *Fitting Curves and Surfaces to Data*. In Monterey, C.A: Wadsworth Advanced Books and Software.

Cleveland, R.B., Cleveland, W.S., McRae, J.E and Terpenning, I.(1990). STL: A Seasonal-Trend Decomposition Procedure Based on Loess. *Journal of Official Statistics,* No 1. pp 3-73.

COAG.(1992). *National Strategy Towards Ecologically Sustainable Development.* Commonwealth of Australia, Canberra.

Cole, J.E., Fairbanks, R.G and Shen, G.T.(1993). Recent variability in the Southern Oscillation: Isotopic results from Tarawa coral atoll. *Science*. Vol.260, 1790-1793.

Commonwealth of Australia.(1996). *State of the Environment, Australia.* State of the Environment Advisory Council. Commonwealth of Australia, Canberra. CSIRO Publishing, ISBN 0 643 05830 3.

Commonwealth of Australia.(1999). *Budget Statements 1998-1999* (AGPS: Canberra).

Commonwealth of Australia.(2001). *Australia State of the Environment Report*, CSIRO Publishing on behalf of the Department of the Environment and Heritage, ISBN 0643 06751 5.

Conway, M.E.(1997). *Pacific Regional Management System. State Innovations Briefs*. In New and Best Practices in State Government. An on-line publication: http://stars.csg.org/innovations_awards/1997_hawaii.pdf

Cook, F.J., Lush, L., Carlin, G.D., Ahern, C.R., Blackwell, J., Mischke L.V and Mischke, K.R.(2002a). Lime Slots for Reducing the Acidity of Drainage Waters from Acid Sulphate Soils. *Environmental Engineering Society Conference*. On-line publication: http://www.eesq.com.au/papers/Lime%20Slots%2002-6E-01(035).pdf

Cook, F.J., Rassam, D.W., Carlin, G.D., Mishke, L and Mishke, K.(2002b). FLASSH-Acid Sulfate Soil Drainage Water Quality Model. *Proceedings of 4th Environmental Engineering Conference*, Brisbane, 30-31 May, 2002

Costa-Carbral, M.C and Burges, S.J.(1994). Digital elevation model networks (DEMON): A model of flow over hillslopes for computation of contributing and dispersal areas. *Water Resources Research*, 30(6): 1681-1692.

Costanza, R, d'Arge, R., de Groot, R.; Farber, S.; Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R., Paruelo, J., Raskin, R.G., Sutton, P and van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*; 387, 253-260.

Costanza, R, d'Age, R., de Groot, R., Faber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R., Paruelo, J.(1998). The Value of Ecosystem Services: Putting the issues in perspective. *Ecological Economics*, 25, 67-72.

Cramer, D., MacPherson, A and Coyle, C.(2002). Managing Acid Sulfate Soils on the Yelgun to Chinderah Pacific Highway Upgrade. *Proceedings of the 5th*

International Acid Sulfate Soils Conference, Tweed Heads, NSW Australia. Pp65-66.

Cravotta, C.A and Trahan, M.K.(1999). Limestone drains to increase pH and remove dissolved metals from acidic mine drainage. *Applied Geochemistry,* 14(5), 581-606.

Creagh, C.(1991). Preventing Acid Spills. *Ecos .70,* Summer 1991/92: 12-16.

Croke, B.(2002). Hydrological Parameterisation of SedNet. *Report by The Integrated Catchment Assessment and Management Centre,* The Australian National University.

Crooks, S and Turner, R.K.(1999). Integrated coastal management: sustaining estuarine natural resource. *Advances in Ecological Research,* 29, 241-289.

Daly, H.E.(1992). *Steady-state Economics.* Earthscan Books: London.

Delbaere, B., Drucker, G and Rientjes, S.(1995). The European Centre for Nature Conservation and World-Wide Web: aspirations for the future. In: *Internet Applications and Electronic Information Resources in Forestry and Environmental Sciences.* Eds: Hannu Saarenmaa and Alois Kempf, EFI proceedings, No 10, European Forest Institute. ISBN 952-9844-23-9, pp 11-18

Delfiner, P and Delhomme, J.P.(1975). Optimum interpolation by kriging. In: J.D.Davis and M.J.McCullagh (eds). *Display and Analysis of Spatial Data.* John Wiley & Sons, New York, pp 96-114.

Densham, P.(1991). Spatial Decision Support Systems. *In Geographical Information Systems: Principles and Applications,* Vol 1. Eds: Maguire, D.J., Goodchild, M.F and Rhind, D.W., Longman UK. Pp 403-412.

Dent, D.(1986). *Acid sulphate soils: A baseline for research and development.* ILRI Pub.No.39, International Institute for Land Reclamation and Improvement, Wageningen.

Dent, D.L and Bowman, G.M.(1993). Definition and quantitive assessment of acid sulphate hazard for planning and environmental management. P 94: In R.Bush (ed), *Proceedings of the National Conference on Acid Sulphate Soils.* Coolangatta, Queensland, 24-25 June 1993.

Dent, D.L and Raiswell, R.W.(1982). Quantitative models to predict the rate and severity of acid sulphate development: A case study in the Gambia. In: H.Dost and N. van Breemen (eds)*: Proceedings of the Bangkok symposium on acid sulphate soils*, 73-95. International Institute for Land Reclamation and Improvement Publication No. 39, Wageningen.

Derek, E.(1996). *Smog Alert: Managing Urban Air Quality* (Earthscan Publications Limited, London. p48

De Roo, A.P.J.(1998). Modelling runoff and sediment transport in catchments using GIS. *Hydrological Processes,* Vol 12, No 6, pp 905-922

Desmier, R., MacDonald, B.C.T., Melville, M.D and Waite, T.D.(2002). Design, Construction and Performance of Passive and Active Treatment Systems to Decrease the Acidity Export from Acid Sulfate Soils in the Tweed Shire, NSW (Australia), *Proceedings of the 5th International Acid Sulfate Soils Conference,* Tweed Heads, NSW Australia. Pp 71-72

DeVantier, B.A and Feldman, A.D.(1993). Review of GIS applications in Hydrologic modeling. *Journal of Water Resource Planning and Management,* 119(2): 246-261.

Diemont, H.H., Pons, L.J and Dent, D.L.(1993). Standard profiles of acid sulphate soils. In D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, 51-59. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

DISR.(2002).*Spatial Information Industry Action Agenda.* Department of Industry Science and Resources Publication, ISBN 0 642 72170 X

DITR.(2002). Department of Industry, Tourism and Resources. *Research Report No 1.* The Australian Tourism Satellite Account. http://www.industry.gov.au/library/content_library/ResearchReport1ATSA.pdf

DLWC.(1998). NSW Department of Land and Water Conservation, *PEENA, Version 6*, New South Wales Surface Water Archive, (CD Rom Version)

Doorn, M and Eliens, A.(1995). Integration applications and the World Wide Web. *Third International WWW Conference 1995: Technology, Tools and Applications.* April 10-14, 1995, Darmstadt, Germany. Computer Networks and ISDN Systems, Volume 27, issue 6.

Dove, M.C.(1997). The Deleterious Effects of Acidified Water on the Sydney Rock Oyster *Saccostrea commercialis.* Honours Thesis, School of Geography, University of New South Wales, NSW.

Dove, C.M., Sammut, J., Callinan, R.B and Bayne, B.(1999). Impacts of acidified water on the Sydney Rock Oyster *Saccostrea commercialis The Annual International Conference and Exposition of the Aquaculture Society*. Sydney Australia.

Dovers, S.(1996). Policy Processes for Sustainability. Unpublished PhD Thesis. Australian National University, Canberra ACT.

DPIE.(1997). Department of Primary Industries and Energy, *The 2020Vision Statement Report*, Canberra, ACT.

Driml, S.(1994). Protection for profit: economic and financial values of the Great Barrier Reef World Heritage Area and other protected areas. *Great Barrier Reef Marine Park Authority Research Publication No 35.*

Driscoll, C.T., Baker, J.P., Bisgoni, J.J and Schofield, C.L.(1980). Effect of aluminium speciation on fish in diluted acidified waters. *Nature*, 284: 161-164.

Drosdowsky, W and Williams, M.(1991). The Southern Oscillation in the Australian region. I: Anomalies at the extremes of the Oscillation. *Journal of Climate*, 4 (6), 619-638.

Eagleson, P.S.(1982). Ecological optimality in water-limited natural soil-vegetation systems, 1, Theory and hypothesis, *Water Resources Research*, 18, 325-340.

Easton, C.(1989). The Trouble with the Tweed. *Fishing World.* Pp58-59.

Easton, C.(1991). Acid Water Monitoring. *Tweed Shire Council Report.* December 1991.

Easton, C.(1992). Cudgen Lake Acidity. *Report to Environment and Community Services.* Tweed Shire Council, May 1991.

Easton, C.(2002). Control of Acid-Water Breeding Mosquitoes, In the Tweed Shire NSW, By Installing Controlled Leakage Holes in Tidal Flap Gates. *5th International Acid Sulfate Soils Conference,* Tweed Heads, Australia.

Egglishaw, H., Gardiner, J.R and Foster, J.(1986). Salmon catch decline and forestry in Scotland. *Scottish Geographical Magazine* 102: 57-61.

Ehrhardt, J.K., Brown, J., French, S., Kelly, G.N., Mikkelsen, T and Muller, H.(1997).'‘RODOS: Decision-making Support for Off-site Emergency Management After Nuclear Accidents. *Kerntechnik,* 62 (2-3); 122-128.

EIS.(1996). *Proposed Forestry Operations in the Murwillumbah Management Areas*, Volume A, State Forest of NSW.

EIS.(1998).*Pacific Highway Upgrade, Yelgun to Chinderah.* Sinclair Knight and Merz.

Elsom, D.(1996). *Smoke Alert: Managing Urban Air Quality.* Earthscan Publications Limited, London. P.48.

Engel, B.A., Srinivasa, R., and Rewerts, C.(1993). Spatial Decision Support Sysytem for Modeling and Managing Agricultural Non-Point Source

Pollution. In: *Environmental Modeling with GIS.* Ed: Goodchild M.F., Parks.B.O., Steyaert.L.T. Oxford University Press New York, Oxford. Pp 231-237..

Engel, B.A., Srinivasan,R., and Rewerts, C.C.(1991). A GIS toolbox approach to hydrologic modeling. *Proceedings, GRASS 1991 User's Conference*, Berkeley, California.

EPA Victoria.(2001). Determination of Financial Assurance for Landfills. *Information Bulletin, publication No 777.*

Eriksson, E.(1993). Modelling flow of water and dissolved substanaces in acid sulphate soils. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, 369-380. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

ESRI.(2002) *ESRI ArcNews, Software News.* Announcing ArcIMS, Summer 2002. P8-10.

Eyre, B and Pepperell, P.(1997). A Spatially Intensive Approach to Water Quality Monitoring in the Rous River Catchment. Centre for Coastal Management, Southern Cross University. *Report to Tweed Shire Council.*

Faber, M., Manstetten, R., Proops, J.(1996). *Ecological Economics: Concepts and Methods.* Edwards Elgar Publishing. UK.

Fairbanks, R.G., Evans, M.N., Rubenstone, J.L., Mortlock, R.A., Broad, K., Moore, M.D and Charles, C.D.(1997). Evaluating climate indices and their geochemical proxies measured in corals. *Coral Reefs,* Vol 16, Suppl., S93-S100.

Fanning, D.S., Snow, P.A., Rabenhorst, M.C and El Desoky, M.A.(1988). Evidence of eluviation-illuviation of sulfur and heavy metals in sulfaquepts in recent Baltimore Harbour (MD) dredged materials. In: H.Dost (ed): *Selected papers of the Dakar symposium on acid sulphate soils*, 38-48. International Institute for Land Reclamation and Improvement Publication No44, Wageningen.

Fanning, D.S and Witty, J.E.(1993). Revisions of soil taxonomy for acid sulphate soils. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils,* 61-69. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Fedorov, A.V and Philander, S.G.(2000). Is El Niño Changing? *Science* 288,1,997-2,002.

Fernandez, G.P., Chescheir, G.M., Skaggs, R.W., Amatya, D.M and Birgand, F.(2001). Modeling poorly drained watersheds with an integrated watershed scale hydrology/water quality model. *ASAE Paper 01-2082, ASAE International Meeting*, Sacramento, CA.

Fitzpatrick, R,W., Hudnell, W.H., Self, P.G and Naidu, R.(1993). Origin and properties of inland and tidal saline acid sulphate soils in South Australia. In D.L. Dent and M.E.F. van Mensvoort (eds): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, 71-80. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen

Forsite.(1989). *Proposed Lake in Coastal Wetland 46A (SEPP14),* Shire of Tweed, New South Wales. Forsite Landscape Architects and Planners Pty Ltd, Environmental Impact Statement.

Folinsbee, L.(1992). Human Health Effects of Air Pollution. Environmental *Health Perspectives*, Vol. 100. pp 47-48.

Frysinger, S.P.(1995). An Open Architecture for Environmental Decision Support. *International Journal of Microcomputers in Civil Engineering*, 10, No.2, pp119-126.

Francis, R.C and Hare, S.R.(1994).Decadal-scale regime shifts in the large marine ecosystems of the North-east Pacific: a case for historical science. *Fisheries Oceanography.* 3(4):279-291.

Garrels, R.M and Thompson, M.E. (1960). Oxidation of pyrite in ferric sulfate solution. *American Journal of Science*, 258:57-67.

Garrett, L.(1994). *The Coming Plague*. Pub Virago Press Limited 1995, London. pp 553.

Gibbs, W.J and Maher, J.V.(1967). Rainfall deciles as drought indicators. *Bulletin 48*. Australian Bureau of Meteorology, Melbourne.

Giblin, A.E.(1988). Pyrite formation in Marshes during early Diagenesis. *Geomicrobiology Journal*, Vol 6:77-97.

Giblin, A.E and Howarth, R.W.(1984). Porewater evidence for dynamcic sedimentary iron cycle is salt marshes. *Limnology Oceanography*. 29: pp 47-63.

Gibson, D.L.(1985). Pyrite-organic matter relationships: current bush limestone, Georgina Basin, Australia. *Geochimica et Cosmochimica Acta*, 49: 989-992.

Goldhaber, M.B. and Kaplan, I.R.(1975). Control and consequences of sulfate reduction rates in recent marine sediments: *Soil Science*, Vol. 119, pp 42-55

Goldhaber, M.B and Kaplan, I.R.(1974). The sulfur cycle. In: E.D.Goldberg (ed.). The sea, Vol. 5, *Marine Chemistry*. John Wiley and Sons, Inc.

Goldhaber, M.B and Kaplan, I.R.(1982). Controls and consequences of sulfate reduction rates in recent marine sediments. In: J.A.Kittrick, D.S. Fanning and L.R. Hossner (eds.): Acid Sulfate Weathering, 19-36. *Soil Science Society of America Special Publication* No. 10, Madison, WI.

Grayson, R.B., Argent, M., Nathan, R., McMahon, T,A and Russell, G.M.(1996). *Hydrological Recipes*. Estimation Techniques in Australian Hydrology, Cooperative Research Centre for Catchment Hydrology Publication. ISBN 1 876006 13 7.

Green, D.(1993). Rivers of Death. *Fishing World*, March. 38-41.

Greiner, R., Young, M.D., McDonald, A.D and Brooks, M.(1997). Australia's Oceans Policy, Oceans Planning and Management Issues. Paper 2, *Management Instruments for Marine Resource Allocation and Use*, Environment Australia. Canberra.

Guariso, G and Werthner, H.(1989). *Environmental Decision Support Systems.* Chichester, Engalnd: Ellis Horwood Books.

Hamilton, A.(1998). *Natural Resource Study of the Tweed River Catchment, Report 1*, Introduction and Methodology, NSW, DLWC.

Hamming, A.F.J and van den Eelaart, A.L.J.(1993). Soil permeability, interflow and actual acidity in acid sulfate soils, South Kalimantan, Indonesis. In D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils,* 51-59. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Hanhart, K and Ni, Doung van.(1993).Water management on rice fields at Hoa An, Mekong Delta, Vietnam. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, 161-175, International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Harremoes, P and Turner, R.K.(2001). Methods for integrated assessment. *Regional Environmental Change*, 2, 57-65.

Harries, J.(1997). *Acid Mine Drainage in Australia. Its extent and future liability.* Supervising Scientist Pyrite Management Program 124. Supervising Scientist, Canberra.

Harris, G.P.(1999). Comparison of the biogeochemistry of lakes and estuaries: ecosystem processes, functional groups, hysteresis effects and interactions between macro- and microbiology. *Marine and Freshwater Research* 50, 791-811.

Harries, K., Harries, S., Heath, L.C., Bergman, I.(1998). Summary of Proposed Local Sewage Treatment Plant at Bundeena. *Report for the Port Hacking Protection Society.* On-line publication:http://www.eidn.com.au/envirotechpublication2.htm

Hayes, T.(1993). Acid Sulphate Soils in the Tweed Valley. *Unpublished Technical Paper,* NSW Sugar Milling Co-operative, Condong Sugar Mill.

Heath, L.C and Bergman, I (1997). Local Sewage Treatment Systems, *Report to Environment Industry Development Network (EIDN).* An on-line publication: (http://www.eidn.com.au/reports/envirotechpublication1.htm)

Hellwege, F.(1996). Centre for Research in Water Resources. *Hydro 97 CD Rom.* The University of Texas, Austin.

Helms, W and Heinrich, D.(1997). Development of backfill material for minimising acid mine drainage generation in abandoned underground mines. *Conference proceedings, Fourth International Conference on Acid Rock Drainage,* Vancouver, B. C., Canada, pp 1251-1266.

Hilbert, A.R.(1967). Forest treatment effects on water yield. In: *Forest Hydrology.* Eds Sopper,W.E and Lull, 813pp., Pergamon, Tarrytown, N.Y.

Hinkley, J.(1990). *Vistapro Version 4.01*

Holder, D., Hutchinson, M.F., Nix, H and McMahon, J.P.(1999).*ANUCLIM User Guide, Version 5.0,* ANU CRES.

Holmes, J.W and Sinclair, J.A.(1986). Water yield from some afforested catchments in Victoria, *Paper presented at Hydrology and Water Resources Symposium, Institute of Engineers,* Brisbane, Australia, Nov 25-27.

Holmgren, P.(1994). Multiple flow direction algorithms for runoff modelling in grid based elevation models: An empirical evaluation. *Hydrological Processes,* 8: 327-334.

Horton, R.E.(1919). Rainfall interception. *Monthly Weather Review,* 47, 603-623.

Howarth, R.W.(1979). Pyrite: Its rapid formation in salt marsh and its importance in ecosystem metabolism. *Science*, 203: 49-51.

Howells, G.P.(1990). Acid Rain and Acid Waters. Ellis Horwood series in *Environmental Science*. P156, Ellis Horwood Ltd, Chichester, West Sussex, ISBN 0-13-004797

Hoy, R.D.(1977). Pan and lake evaporation in Northern Australia. In: *Proceedings of Hydrology Symposium, Brisbane*, *Institute of Engineers*, Australia. pp 57-61

Hoy, R.D and Stephens, S.K.(1977). Field study of lake evaporation-analysis of data from Eucumbene, Cataract, Manton and Mundaring. Australian Water Resources Council. *Technical paper No 21*.

HRC.(2002). Healthy Rivers Commission of New South Wales. *Independent Public Inquiry into Coastal Lakes*. 74 pp.

Hunter, G.J and Goodchild, M.F.(1995). Dealing with error in spatial databases: a simple case study. *Photogrammetric Engineering and Remote Sensing* 61: 529-537.

Hutchinson, M.F.(1989). A method for gridding elevation and stream line data with automatic removal of spurious pits. *Journal of Hydrology* 106: 211-232.

Hutchinson, M.F.(1991). The application of thin plate smoothing splines to continent-wide data assimilation. In: *Data Assimilation Systems*, J.D. Jasper (ed), Bureau of Meteorology Res. Rep No. 27, Bureau of Meteorology, Melbourne, pp. 104-113.

Hutchinson, M.F and Dowling, T. I.(1991). A new method for gridding elevation and stream line data with automatic removal of pits. *Hydrological Processes* 5, 45-58.

Hutchinson, M.F.(1993). On thin plate splines and kriging. In: Tarter, M.E. and Lock, M.D. (eds), *Computing Science and Statistics* Vol.25, Interface Foundation of North America, University of California, Berkeley, 55-62.

Hutchinson, M.F and Gessler, P.E.(1994). Splines- more than just a smooth interpolator. *Geoderma* 62: 45-67.

Hutchinson, M.F.(1995). Interpolating mean rainfall using thin plane smoothing splines. *International Journal of GIS* 9:385-403.

Hutchinson, M.F.(1996). A locally adaptive approach to the interpolation of digital elevation models. *Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling.* National Center for Geographical Information and Analysis, Santa Barbara, CA. CD-ROM and World Wide Web. http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/main.html.

Hutchinson, M.F.(1997). ANUDEM Version 4.6 User Guide. Centre for Resource and Environmental Studies, Australian National University.

Hutchinson, M.F.(1998). Modelling Spatial and Temporal Variability of Climate and Terrain. In:*Spatial and Temporal Variability in Catchment Hydrology: Use of Models and GIS Systems.* Centre for Resource and Environmental Studies, Australian National University, Canberra, ACT.

Hutchinson, M.F.(2002a).*ANUDEM Version 4.6.3.* Centre for Resource and Environmental Studies, Australian National University. http://cres.anu.edu/outputs/anudem.html

Hutchinson, M.F.(2002b).*ANUSPLIN Version 4.2* Centre for Resource and Environmental Studies, Australian National University. http://cres.anu.edu/outputs/anusplin.html

IGBP.(2001). Global change and the earth system: a planet under pressure. IGBP Science No 4., 32pp. *International Geosphere-Biosphere Program*, Stockholm, Sweden.

IPCC.(1990). *Climate Change*. The IPCC Scientific Assessment. Report prepared for the IPCC working group. Eds: Houghton, J.T, Jenkins,G.J and Ephraums, J.J

Jacqmin-Gadda, H., Commenges, D., Letenneur, L and Dartigues, J.F.(1996). Silica and aluminum in drinking water and cognitive impairment in the elderly, *Epidemiology,* 7(3):281-5.

Jenson, S.K and Domingue, J.O.(1988) Extracting topographic structure from digital elevation data for geographic information system analysis, *Photogrammetric Engineering and Remote Sensing,* 54: 1593-1600.

Johnston, P.L.W.(1999). The distribution and amount of soil acidity in the lower Cudgen Lake Catchment, BSc Honours Thesis, School of Geography, UNSW.

Jones, P.D., New, M., Parker, D.E., Martin, S and Rigor, I.G.(1999). Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, 37, pp173-199.

Jones, R.N and Pittock, A.B.(1997). Assessing the impacts of climate change: the challenge for ecology. CSIRO Division of Atmospheric Research. *On line publication*: http://life.csu.edu.au/esa/esa97/papers/jones/jones.htm

Kaplan, I.R and Rittenberg, S.C.(1964). Microbiological fractionation of sulfur isotpoes. *Journal of General Microbiology*, 34: 195-212.

Keig, G and Mc Alpine, J.R.(1974). WATBAL: a computer system for the estimation and analysis of soil moisture regimes from simple climatic data. *Technical Memo 74/4*. CSIRO Australia, Division Land Use Research.

Kim, D.J., Diels, J and Feyen, J.(1992). Water movement associated with overburden potential in a shrinking marine clay soil. *Journal of Hydrology*, 133, 238-245.

Kremer, H and Crossland, C.(2002). Coastal change and the "Anthropocene" Past and Future Perspectives of the IGBP – LOICZ project. *International Conference on Low-lying Coastal Areas Hydrology and Integrated Coastal Zone Management,* Bremerhaven, federal republic of Germany, 9-12 September 2002.

Kselik, R.A.L., Smilde, K.W., Ritsema, H.P., Kasdi, Subagyono., Saragih, S., Mauliana Damanik and Suwardjo, H.(1993). Intergrated research on water management, soil fertility and cropping systems on acid sulphate soils in South Kalimantan, Indonesia. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, 177-194, International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Lacey, D.T and Lawson, F.(1970). Kinetics of the liquid –phase oxidation of acid ferrous sulfate by the bacterium *Thiobacillus ferrooxidans. Biotechnology and Bioengineering*, 12: 29-50.

Lane, W.N.(1983). *Community and Regional Planning*, In Standard Handbook for Civil Engineers, ed. by Merritt F.S., 3rd. Ed., McGraw-Hill Inc., New York, pp. 14.1-14.46.

Langfield, K., Thorne, H and Hilton, R.W.(1998). *Management Accounting: An Australian Perspective* (second edition). McGraw-Hill Book Company. ISBN 0 074705016

Latif, M and Barnett, T.P.(1996). Decadal Climate Variability Over the North Pacific and North America: Dynamics and Predictability, *Journal of Climate*, 9, 2407-2423.

Latif, M and Barnett, T.P.(1994). Causes of decadal climate variability over the north Pacific and North America. *Science* 266, 634-637.

Laut, P.(1971). Special Article- Changing patterns of land use in Australia, CSIRO Division of Water and Land Resources. In *Year Book Australia, ABS Publication, Catalogue No. 1301.0*

Lea, F.M.(1968). Some studies on the performance of concrete structures in sulphate bearing environments. In: E.G. Swenson (ed.). *Performance of Concrete*. A Symposium in Honour of Thorbergur Thorvaldson. University of Toronto Press, Canada. 243 pp.

Lea, F.M.(1997). Action of acid sulphate waters on Portland cement, in *Chemistry of Cement and Concrete*, 3rd ed. E. Arnold, New York. p 338-360.

Leung, Y.(1997). *Intelligent Spatial Decision Support Systems*. Berlin, Germany: Springer-Verlag.

Lilley, J.H., Phillips, M.J and Tonguthai, K.(1992). *A Review of Epizootic Ulcerative Syndrome (EUS) in Asia*. Aquatic Animal Health Research Institute and Network of Aquaculture Centres in Asia-Pacific, Bangkok, Thailand. pp 73.

Lin, C and Melville, M.D.(1992). Mangrove soil: potential contamination source to estuarine ecosystems of Australia. *Wetlands (Australia)*, 11:68-75.

Lin, C., Melville, M.D., White, I and Wilson, B.P.(1995). Human and natural controls on the accumulation, acidification and drainage of pyritic sediments: Pearl River Delta, China and Coastal New South Wales. *Australian Geographical Studies* 33 (1) pp77-88.

Lowe, I.(1994). Performance Measurement. *Proceedings of the Fenner Conference on the Environment, November 1994.*

Lowenstein, W.(2001). Environmental and Economic Accounting. Course on National Accounts. *No-line publication*: http://www.cdg-fz.de/coursematerial/k57/16-EnvEco.pdf

Luther, G.W., Giblin, A.E and Varsolona, R.(1985). Polarographic analysis of sulfur species in marine porewaters. *Limnology Oceanography*. 30: pp727-736.

Macdonald, B.C.T., Denmead, O.T., White, I and Melville, M.D. (2004). Natural sulfur dioxide emissions from sulfuric soils. *Atmospheric Environment,* 38 pp 1473-1480.

MacEachren, A.M.(1994). Visualisation in modern cartography: setting the agenda, in *Visualisation in Modern Cartography* (NY: Elservier Science Inc.),pp. 1-12.

Mackinlay, J.(1986). Automating the Design of Graphical Presentation of Relational Information. *ACM Transactions on Graphics* 5, 110-141.

Maidment, D.R (1993). GIS and Hydrological Modelling. In: *Environmental Modeling with GIS.* Ed: Goodchild M.F., Parks.B.O., Steyaert.L.T. Oxford University Press New York, Oxford. Pp 147-167.

Mantua, N.J., Hare, S.R., Zhang,Y., Wallace, J.M and Francis, R.C.(1997). A Pacific Interdecadal Climate Oscillation with Impacts of Salmon, *Bulletin of American Meteorological Society,* 78, 1069-1079.

Mantua, N.J.(2002). Pacific-Decadal Oscillation (PDO). The Earth system: physical and chemical dimensions of global environmental change, Vol 1, pp592-594 (Eds) M.C..MacCraken and J.S.Perry In: *Encyclopedia of Global Environment Change Vol 1.* John Wiley and Sons, Ltd, Chichester.

Mark, D.M.(1984). Automated detection of drainage networks from digital elevation models, *Cartographica*, 21: 168-178.

Martz, L.W and Garbrecht, J.(1992). Numerical Definition of Drainage Network and Subcatchment Areas from Digital Elevations Models. *Computers and Geoscences,* 18(6): 747-761.

Martz, L.W and Garbrecht, J. (1995). Automated Recognition of Valley Lines and Drainage Networks from Grid Digital Elevation Models: A Review and a New Methods. Comment. *Journal of Hydrology*, 167 (1): 393-396.

McBride, J.L and Nicholls, N.(1983) Seasonal relationships between Australian rainfall and the Southern Oscillation. *Monthly Weather Review.* 111, 1998-2001.

McCormick, B.H., DeFanti, T.A and Brown, M.D.(1987). Visualization in Scientific *Computing, Computer Graphics,* Vol. 21, No. 6.

Milankovitch, M.M.(1941). Canon of Insolation and the Ice Age Problem. *Königlich Serbische Academie*, Belgrade. English translation by the Israel Program for Scientific Translations, United States Department of Commerce and the National Science Foundation, Washington D.C.

Mobbs, M.(1996). *Incentives for Restoring and Keeping Vegetation: A guide for Australian Landholders and Governments.* Commonwealth Department of Primary Industries and Energy.

Moore, P.A and Patrick, W.H.(1989a). Calcium and magnesium availability and uptake by rice in acid sulphate soils. *Soil Science of America, Journal*, 53:816-822.

Moore, P.A and Patrick, W.H.(1989 b). Iron availability and uptake by rice in acid sulphate soils. *Soil Science Society of America, Journal,* 53:471-476.

Moore, P.A., Attanandana, T and Patrick, W.H. (1990) *Soil Science Society of America Journal.* 54: 1651-1656.

Moore, I.D., Grayson, R.B and Ladson, A.R.(1991). Digital Terrain Modelling: A Review of Hydrological, Geomorphological and Biological Applications. *Hydrological Processes*, 5 (1): 3-30.

Moore, I.D., Turner, A.K., Wilson, J.P., Jenson, S.K and Band, L.E.(1993). GIS and Land-Surface –Subsurface Process Modeling. In: *Environmental Modeling with GIS.* Ed: Goodchild M.F., Parks.B.O., Steyaert.L.T. Oxford University Press New York, Oxford. Pp 196-230.

Moorse, J.W., Millero, F.J., Cornwell, J.C and Rickard, D.(1987). The Chemistry of the Hydrogen Sulfide and Iron Sulfide Systems in Natural Waters. *Earth Science Reviews,* 24. 1-42.

Morand, D.T.(1996). *Soil Landscapes of the Murwillumbah- Tweed Heads 1:100 000 sheet Report*, DLWC, Sydney.

Moy, C.H., Seltzer, G.O., Rodbell, D.T and Anderson, D.A.(2002). Variability of El Niño/Southern Oscillation activity at millennial timescles during the Holocene apoch. *Nature*, Vol 420, 162-165.

Mues, C., Chapman, L and Van Hilst, R.(1998). Promoting improved land management practices on Australian farms. *A survey of Landcare and land management related programs, ABARE research report 98.4,* Australian Bureau of Resource Economics, Canberra.

Muhrizal Sarwani., Mansur Lande and Andriesse, W.(1993).Farmers' experiences is using acid sulphate soils: Some examples from tidal swampland of southern Kalimantan, Indonesia. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils,* 113-121. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Mullen, J.D and Kaur, P.(1999). ASS and the Agricultural Sector in NSW: A report to ASSMAC, March 1999. *NSW Agriculture, unpublished report.*

Mullroy, I.C and Angus, D.E.(1964). Grass water and soil evaporation at Aspendale, *Agricultural Meteorology.* 1, pp 201-224.

Murphy, N. C., Taylor, J. R and Leake, M. J.(1999). Coming to terms with acid drainage. *Proceedings of the "State of the Art in Mining Environmental Management",* Manilla, Philippines.

National Parks and Wildlife ACT.(1974). NSW National Parks and Wildlife Service. No 80.

http://www.legislation.nsw.gov.au/viewtop/inforce/act+80+1974+FIRST+0+N

Naylor, S.D., Chapman, G.A., Atkinson, G., Murphy, C.L., Tulau, M.J., Flewin, T.C., Milford, H.B and Morand, D.T.(1995). *Guidelines for the use of acid sulfate soil risk maps,* 1st ed., Department of Land and Water Conservation, Sydney.

Naylor, S.D ., Chapman, G.A., Atkinson, G., Murphy, C.L., Tulau. M.J., Flewin, T.C., Milford, H.B and Morand, D.T.(1998). *Guidelines for the use of acid sulfate soil risk maps*, 2nd ed., Department of Land and Water Conservation, Sydney.

Nguyen Thi., Thanh Phung and Phan Lieu.(1993). Microbiological Characterisation of Acid Sulphate Soils: a case study in Ho Chi Minh City environs. In:D.L.Dent and M.E.F.van Mesnsvoort (eds.). *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils* pp.341-356. International Institute for Land Reclamation and Improvement: No.53, Wageningen.

Nguyen Thanh Tin and Wilander, A.(1995). Chemical conditions in acidic waters in the plain of reeds, Vietnam. *Water Resources*, 29: 1401-1408.

Nichols, R.L., Looney, B.B and Huddleston, J.E.(1992). 3-D digital imaging. *Environmental Science and Technology*, 26: 642-9.

Nicholls, N., Drosdowsky, W and Lavery, B.(1997). Australian rainfall variability and change. *Weather*, Vol 52, 66-72.

Nicholls, N.(1985). Impact of the Southern Oscillation on Australian crops. *Journal of Climatology,* 5, 553-560.

Nicholls, N.(1988). More on early ENSOs: Evidence from Australian documentary sources. *Bulletin American Meteorological Society*, 69, 4-6.

Nicholls, N.(1987).El Niño-Southern Oscillation and Rainfall Variability. *Journal of Climate* Vol, 418-422.

Nicholls, N and Wong, K.K.(1990). Dependence of rainfall Variability on Mean Rainfall, Latitude and the Southern Oscillation. *American Meteorological Society.* Vol 3: 163-171

Nicholls, N., Lavery, B.B., Frederiksen, C., Drosdowsky, W and Toroks, S.(1996). Recent apparent changes in relationships between the El Niño-Southern Oscillation and Australian rainfall and temperature. *Geophysics Research Letters*, 23, pp 3357-3360.

Nigam, S., Barlow, M and Berbery, E.H.(1999). Analysis Links Pacific Decadal Variability to Drought and Streamflow in the United States, *EOS American Geophysical Union,* 80 (51)

Nordstrom, D.K.(1982). Aqueous pyrite oxidation and the consequent formation of secondary minerals. In: Kittrick, J.A. (ed). *Acid Sulphate Weathering*, pp 37-56. SSSA Special Publication, No 10, Madison, WI, USA.

Nriagu, J.O.(1978). Dissolved silica in pore waters of Lake Ontario, Erie and Superior sedimnets. *Limnology and Oceanography,* 23: 53-67.

NSW Agriculture.(2001). Macleay River Catchment. *ASS Remediation Projects Review Workshop*, Kempsey, May 2001.

NSW Agriculture.(2002). *Review of ASSPRO Workshop*, Port Macquarie, May 9, 2002.

NWPASS.(1999). *National Strategy for the Management of Coastal Acid Sulfate Soils 1999.* National Working Party on Acid Sulfate Soils. NSW Agriculture, Wollongbar.

O'Callaghan, J.F and Marks, D.M.(1984). The extraction of drainage networks from digital elevation data, *Computer Vision Graphics and Image Processing*, 28, 323-344.

Olivera, F., Maidment, D.R and Charbeneau, R.J.(1997). Spatially Distributed Modeling of Storm Water Runoff and Non Point Source Pollution using Geographic Information Systems. *CRWR Online Report 96-4,* December

1996. University of Texas at Austin Center for Research in Water Resources. http://www.ce.utexas.edu/prof/olivera/disstn/header.htm

Olivera, F and Maidment, D.R.(1997). *Storm Runoff Computation Using Spatially Distributed Terrain Parameters.* University of Texas at Austin Center for Research in Water Resources.http://www.ce.utexas.edu/prof/olivera/impr_uh/impr_uh.htm

Palko, J and Weppling, K.(1995). Modelling the effects of Acid Sulfate Soils on River Acidity in Finland. *Nordic Hydrology*, 26: 37-54

Palmer, W.C.(1965). Meterorological drought. *Research paper No.45.* United States Weather Bureau.

Pease, M.I.(1995). Acid sulphate soils and acid drainage, lower Shoalhaven Floodplain, NSW. MSc (Hons.) Thesis, Department of Geography, University of Wollongong.

Pearce, F.(1995). Death and Devil's Water. *New Scientist*, 16 September, pp14-15.

Pearce, M.(1990). Epizootic Ulcerative Syndrome Technical Report, December 1987- September 1989. Northern Territory Department of Primary Industries and Fisheries. *Fisheries Report No .22.* Darwin.

Pearce, D.(1993). *Economic Values and the Natural World*, Earthscan, London.

Pearson, F.H and McDonnell, A.J.(1975). Limestone barriers to neutralise acidic streams. *Journal of the Environmental Engineering Division*, ASCE 101, No EE3, p 426-440.

Penman, H.L.(1948). Natural evaporation from open water, bare soil and grass. *Proceedings Royal Society London Series A* 193, 120-145.

Pernetta, J.C and Milliman, J.D.(1995). Land-Ocean Interactions in the Coastal Zone- Implementation Plan. *IGBP Global Change Report No 33. International Geosphere-Biosphere Programme*, Stockholm, Sweden, 215pp.

Pesic, B., Oliver, D.J and Wichlacz, P.(1989). An electrochemical method of measuring the oxidation rate of ferrous to ferric iron with oxygen in the presence *Thiobacillus ferrooxidans. Biotechnology and Bioengineering*, 33: 428-439.

Peters,A.,Goldstein.L.F.,Beyer.U.,Franke.K.,Heinrich.J.,Dockery.D.,Spengler.J.D and Winchmann, H.E.(1996). Acute Health effects of Exposure to High Levels of Air Pollution in Eastern Europe. *American Journal of Epidemiology,* Vol 144, No 6. Pp 570-581

Peuker, T.K, Fowler, R.J and Mark, D.M.(1978).The triangulated irregular network. In: proceedings of the DTM Symposium, *American Society of Photogrammetry, American Congress on Survey and Mapping, St Louis, Missouri*, pp24-31.

Philip, J.R.(1969a). Hydrostatics and hydrodynamics in swelling soils. *Water Resources Research*, 5, 1070-1077.

Philip, J.R.(1969b). Moisture equilibrium in the vertical in swelling soils, 2 applications, *Australian Journal of Soil Research*, 7, 121-141.

Philip, J.R.(1970). Hydrostatics and hydrodynamics in swelling soils. Reply to Youngs and Towner. *Water Resources Research*, 6, 1248-1251.

Piwowar, J.M and LeDrew, E.F.(1990). Integrating Spatial Data. A user's Perspective, *Photogrammetric Engineering and Remote Sensing*, 56(11):pp 1497-1502.

Pons, L.J., van Breemen, N and Driessen, P.M.(1982). Physiography of coastal sediments and development of potential soil acidity. In: Kittrick, J.A. (ed). *Acid Sulphate Weathering*, pp 1-18. SSSA Special Publication, No 10, Madison, WI, USA.

Pons, L.J and van Breemen, N.(1982). Factors influencing the formation of potential acidity in tidal swamps. In: H.Dost and N.van Breemen (eds): *Proceedings of the Bangkok Symposium on Acid Sulphate Soils*, 37-51.

International Institute for Land Reclamation and Improvement Publication No.39, Wageningen.

Pons, L.J., van Mensvoort, M.E.F and Le Quang Tri.(1989). A proposal for the classification of mineral Vietnamese acid sulphate soils according to Soil Taxonomy. *Acid Sulphate Newsletter No 2,* November 1989, pp 6-10.

Pons , L.J.(1988). Should acid sulphate soils be classified among the Inceptisols or the Entisols? In: In: *Selected Papers of the Dakar Symposium on Acid Sulphate Soils.* (Ed H. Dost.) pp.90-96. (International Institute for Land Reclamation and Improvement; Wageningen).

Power, S., Casey, T., Folland, C., Colman, A and Mahta, V.(1999a). Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics,* 15: 319-324.

Power, S., Tseitkin, F., Mehta, V., Lavery, B., Torok, S and Holbrook, N.(1999b). Decadal Climate Variability in Australia During the Twentieth Century. *International Journal of Climatology*, 19: 169-184.

Pruitt, W.O.(1966). Emperical method of estimating evapotranspiration using primarly evaporation pans. In: Evaporation and its role in Water Resources Management, *American Society of Agriculture Engineering*, St, Joseph, Mich, pp57-61.

Quenzer, A.M.(1998). A GIS Assessment of Total Loads and Water Quality in the Corpus Christi Bay System. *CRWR Online Report 98-1*, May 1998. University of Texas at Austin Center for Research in Water Resources. http://www.ce.utexas.edu/centre/crwr/reports/online.html

Quinn, P., Beven, K., Chevallier, P and Planchon, O.(1991). The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models, *Hydrological Processes,* 5: 59-79.

RACAC.(1995). *Regional Report of upper north east New South Wales, Volume 3-water attributes.* A report initiated by the Natural Resources Audit Council. Resource and Conservation Assessment Council, Sydney.

Raiswell, R.(1993). Kinetic controls on depth variations in localised pyrite formation. *Chemical Geology*, 107: 467-469

Rasmusson, E.M and Carpenter, T.(1982): Variations in Tropical Sea Surface Temperature And Surface Wind Fields Associated With the Southern Oscillation/El Niño. *Monthly Weather Review* 110, 354-384.

Rassam, D.W and Cook, F.J.(2001). Modelling the Transport of $SO_4{}^{2-}$ Ions in Acid Sulphate Soils. *Congress on Modelling and Simulation, MODSIM 2001*, Australian National University, Canberra, 10-13 December 2001. Pp 499-504. Editors: F.Ghassemi, D.Post, M. Sivapalan and R. Vertessy.

Rennick, G and Jarman, F.C.(1992). Are Children with asthma affected by smog? *Medical Journal of Australia*, 156: 837-41.

Richard, D.(1999).Web Atlases- Internet Atlas of Switzerland. In: Cartwright, W, Peterson,M, Gartner, G,. *Multimedia Cartography.* Berlin, Heidelberg, New York Springer 2000. Pp 113-118.

Richard, G.P and Evans, D.W.(2000a). CAMFor User Manual Vol 3.35 National Carbon Accounting System Technical Report No 26 *Australian Greenhouse Office*, Canberra 47pp.

Richard, G.P and Evans, D.W.(2000b*). CAMAg User Manual Vol 3.35 National Carbon Accounting System*, Australian Greenhouse Office, Canberra. Online Report: http://www.greenhouse.gov.au/ncas/reports/tr28final.html

Ripley, B.D.(1984). Present position and future developments: Some personal views – Statistics in the natural sciences; In *Journal Royal Society* (A), 147: 2:340-348.

Ropelewski, C.F and Halpert, M.S.(1987). Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Monthly Weather Review*, 115, 1606-1626.

Roth, S.M and Mattis, J.(1990). Data Characterisation for Intelligent Graphics Presentation. *Proceedings on Special Interest Group on Computer- Human Interactions (SIGCHI 1990):* Human Factors in Computing Systems. ACM Press 193-200.

Roy, P.S.(1975). Coastal Geology of the Cudgen Area, North Coast of New South Wales. *Records of the Geological Survey of New South Wales.* 17: 41-53.

Roy, P.S.(1984a). Holocene sedimentation histories of estuaries in south eastern Australia, Estuarine environments of the Southern Hemisphere, *Bulletin 161*, 23 – 59, Department of Conservation and Environment, Perth, Australia.

Roy, P.S.(1984b).“New South Wales Estuaries: Their Origin and Evolution ”.In B.G.Thom (ed) *Coastal Geomorphology in Australia.* Academic Press, Australia, pp 99-121.

Roy, P.S and Thom, B.G.(1981). Late Quaternary Marine Deposition in New South Wales and Southern Queensland – An Evolutionary Model. *Journal of Geological Society of Australia*, 28: 471-489.

Sammut, J., Callinan, R.B and Fraser, G.C.(1993). The impact of acidified water on freshwater and estuarine fish populations in acid sulphate soil environments. In: R. Bush (ed.): *Proceeding of the National Conference on Acid Sulphate Soils, 36-40.* Coolangatta, Australia.

Sammut, J., White, I and Melville, M.D.(1994). Stratification in acidified coastal floodplain drains. *Wetlands (Australia),* 13: 49-64.

Sammut, J., White, I and Melville, M.D.(1996). Acidification of an Estuarine Tributary in Eastern Australia due to Drainage of Acid Sulfate Soils. *Marine Freshwater Research,* 47, pp 669-84.

Sammut, J.(1998). Associations between acid sulfate soils, estuarine acidification and gill and skin lesions in estuarine and freshwater fish. Unpublished PhD. Thesis, School of Geography, UNSW.

Satawathananont, S.(1986). Redox, pH and ion chemistry of acid sulfate rice soils in Thailand. PhD Thesis. Louisiana State University.

Saunders, W.K and Maidment, D, R.(1995). Grid-Based Watershed and Stream Network Delineation for the San Antonio-Nueces Coastal Basin, presented at *Texas Water '95*, August 14-18, San Antonio, Texas.

Signor, A.(2001). Farm Forestry NSW: Trees for Coastal Regions and Nearby Ranges. Ed: Murray, C, *NSW Department of Agriculture. Ag Note DPI-377.* ISSN 1034-6848

Silfer, A.T., Kinn, G.J and Hassett, J.M.(1987). A geographic information system utilising the trangulated irregular network as a basis for hydrological modeling. *Proceeding, Auto-Carto 8*, Baltimore, Maryland, pp. 129-136.

Singh ,V.P., Poernomo, A.T and Brinkman, R.(1988). Reclamation and management of brackish water fish ponds in sulfate soils: Philippine experience. In: '*Selected Papers of the Dakar Symposium on Acid Sulphate Soils*'. (Ed H. Dost.) pp.214-228. (International Institute for Land Reclamation and Improvement; Wageningen.

Singer, P.C and Stumm, W.(1970). Acid mine drainage: the rate determining step. *Science*, 167: 1121-1123.

Skaggs, R.W.(1980). A water management model for artificially drained soils. N.C *Agricultural Research Service*, Technical Bulletin No 267, N.C State University.

Smiles, D.E and Poulos, H.G.(1969). One-dimensional consolidation of soils of finite length. *Australian Journal of Soil Research*, 6, 237-248

Smiles, D.E.(1973). An examination of settlement data for an embankment on wet light clay. *Australian Road Research.* 5, 55-59

Smiles, D.E.(2000). Hydrology of swelling soils: A review. *Australian Journal of Soil Research,* 38, 501-521.

Smith, D.I., Hutchinson, M.F and McArthur, R.J.(1992). *Climate and Agricultural Drought Payments and Policy Report on Grant ANU-5A to Rural Industries Research and Development Corporation,* Centre for Resource and Environmental Studies ANU.

Smith, D.I.(1998). *Water in Australia: Resources and Management.* Oxford University Press, Melbourne, 384pp.

Smith, J.(1999a). An Assessment of Spatial Variations in Actual Acidity at McLeods Creek. Unpublished Honours Thesis, School of Geography, UNSW.

Smith, R.(1999b). Floodgates and Drains: Possible improvements in management. *Information Bulletin No 2* February 1999. Hastings Estuary Management Committee.

Smith, R., Sammut, J and Dove, M.(1999*). Impacts of acid water drainage on the Manning OysterIndustry*, Feb 1999,. Manning Oyster farmers Association. Taree, NSW.

Smith, D.(2002). Andes give up some El Niño secrets. *Sydney Morning Herald.* 14 November.

Soils Survey Staff.(1990). Keys to Soil Taxonomy, Fourth Edition. *Department of Soil and Crop Environmental Sciences.* Virginia Tech, Backsburg.

Soils Survey Staff.(1994). *Keys to Soil Taxonomy*, Sixth Edition. United States Department of Agriculture, Soil Conservation Service, Washington, D.C.

Soros-Longworth and McKenzie.(1980*). New South Wales Coastal Rovers Flood Plain Management Studies*. Tweed River.

State Pollution Control Commission.(1987). Water Quality in the Tweed-Terranora Estuary. *Northern Rivers Study No1.*

Stein, J.L., Stein, J.A and Nix, H.A.(1998). *The Identification of Wild Rivers. Methodology and database development.* A report for the Australian Heritage Commission by the Centre for Resource and Environmental Studies, Australian National University.

Stone, Y., Ahern, C.R and Blunden, B.(1998). *Acid Sulfate Soils Manual.* Acid Sulfate Soils Management Advisory Committee, Wollongbar, NSW.

Stoner, J.H and Gee, A.S.(1985). Effects of forestry on water quality and fish in Welsh rivers. *Journal of Water Engineering Science*, 39: 27-45.

Sullivan, L.A and Bush, R.T.(2002). Chemical Behaviour of Monosulfidic Black Oozes (MBOs) In Water: pH and Dissolved Oxygen. *Proceedings of the 5th International Acid Sulfate Soils Conference,* Tweed Heads, NSW Australia, August 25-30 th. Pp14-15.

Sullivan, L.A., Bush, R.T and Ward, N.J.(2002). 'Sulfidic sediments and salinisation in the Murray–Darling Basin' in Proceedings of the Sustainable Management of Acid Sulfate Soils, *5th International Acid Sulfate Soils Conference,* Tweed Heads, NSW Australia, August 25–30th. Pp 196-197.

Swann, C.E.(1993). South America, the promise and the problems. *International Papermaker.* August pp. 23-31.

Taylor, J. R., Waring, C. L., Murphy, N. C and Leake, M. J.(1997). An overview of acid mine drainage control and treatment options including recent advances. In *Proceedings of the Third Australian Acid Mine Drainage Workshop.* Darwin, 15-18 July 1997. (Australian centre for Minesite Rehabilitation Research: Brisbane).

Terry, N. G.(1996). How to Read the Universal Transverse Mercator (UTM) Grid *GPS World,* April Ed. Pp32-33.

Terzaghi, K.(1923).Die Berechung der Durchlassigkeitziffer des Tones auf dem Verlauf der Hydrodynamischen Spannungsercheinungen. *Akad. Wissenchaften in Wein Stizumgberichte, Mathematisch-Naturewissenschaftliche Klasse*. Part Iia, 132,3-4,125-138.

Thom, B. G and Chappell, J.M.A.(1975). Holocene sea levels relative to Australia. *Search,* 6: 90-93.

Tisdell, C.A.(1993). *Environmental Economics: Policies for Environmental Management and Sustainable Development.* Aldershot, Hants, England Brockfield, Vt, USA: Edward Elga. ISBN 1852786396

Toth, D.J and Lerman, A.(1977). Organic matter reactivity and sedimentation rates in the ocean: *American Journal of Science*, Vol 277, pp 265-285.

Traaen, T.S., Frogner, T., Hindar, A., Kleivan, E., Lande, A and Wright, R.F.(1997). Whole catchment liming at Tjonnstrond, Norway – an 11 year record. *Water, Air & Soil Pollution*. 94: 163-180.

Treshow, M.(1984). Impacts of Atmospheric Pollution on Agriculture. In*: Air Pollution and Plant Life.* Pp 368-369. John Wiley and Sons.

Troup, A.J.(1965).The Southern Oscillation . *Quarterly Journal of the Meteorological Society*, 91. 490-506

TSC.(1998). Minutes of Tweed Shire Council, 2 September 1998, p 186-87.

TSC.(2001). *Cudgen Lake Catchment ASS Hotspot Long-Term Management Concept Plan.* Tweed Shire Council.

Tudhope, A.W Chilcott., C.P., McCulloch., M.T., Cook, E.R., Chappell, J., Ellam, R.M., Lea, D.W., Lough, J.M and Shimmield, G.B.(2001). Variability in the El Niño—Southern Oscillation through a glacial–interglacial cycle, *Science*, 291, 1511–151

Tulau, M.J.(1999a). *Acid Sulfate Soil Management Priority Areas in the Lower Tweed Floodplains Report.* Department of Land and Water Conservation, Sydney.

Tulau, M.J.(1999b). *Policy, Strategies and Processes for the Remediation of Acid Sulfate Soil Management priority Areas in New South Wales, Australia.* NSW Department of Land and Water Conservation, Sydney.

Tufte, E.R.(1983). *The Visual Display of Quantitative Information.* Graphics Press, Cheshire Connecticut 06410.

Tuong, To Phuc.(1993). An overview of water management of acid sulphate soils. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, 265-279. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Turner, R.K, Adger, W.N and Lorenzoni, I.(1998). Towards Integrated Modelling and Analysis in Coastal Zones: Principles and Practice. *LOICZ Reports & Studies NO 11*, 122pp. LOIC IPO Texel, The Netherlands.

Turner, K.M.(1991a). Annual evapotranspiration of native vegetation in a Mediterranean-type climate, *Water Resources Bulletin*, 27, 1-6.

Turner, K.R.(1991b). Economics and Wetland Management, *AMBIO.* Vol 20 pp59-63.

Turner, K.R., Pearce, D and Bateman, I.(1994). *Environmental Economics: An Elementary Introduction.* The John Hopkins University Press. UK.

Tweed Link.(2002). Tweed Shire Council Publication, *Issue 256.* ISSN, 1327 8630

UNEP.(1995). *Guidelines for Integrated Management of Coastal and Marine Areas*, UNEP Report.

UNSO.(1990). *SNA Handbook on Integrated Environmental and Economic Accounting*, Statistical Office of the United Nations, New York.

U.S. Army.(1987). *GRASS-GIS Software and Reference Manual*, Champaign, IL: U.S.Army Corps of Engineers, Construction Engineering Research Laboratory.

Van Breemen, N.(1973a). A detailed survey on the actual and potential soil acidity at the Bang Paking land development centre, Thailand. In: Dost, H. (ed.). *Acid Sulphate Soils. Proceedings of the International Symposium*, Vol 2: 159-168. International Institute for Land Reclamation and Improvement Publication No. 18, Wageningen.

Van Breemen, N.(1973b). Soil forming processes in acid sulfate soils. In: Dost, H. (ed.). *Acid Sulfate Soils. Proceedings of the International. Symposium.* Vol. 1.pp 66-130. International Institute for Land Reclamation and Improvement Publication, No 18, Wageningen.

Van Breemen, N.(1982). Genesis,morphology and classification of acid sulphate soils in coastal plains. In: J.A. Kittrick, D.S.Flanning and L.R.Hossner (eds.): *Acid Sulfate Weathering*, pp 95-108. Soil Science Society of America Special Publication No. 10, Madison, WI.

Van Breemen, N.(1988). Redox processes of iron and sulfur involved in the formation of acid sulfate soils. In: Stucki, J.W., Goodman, B.A and Schwertmann, U.(eds). *Iron in soils and clay minerals.* pp825-841. Reidel, Dordrecht.

Van Breemen, N.(1993). Environmental aspects of acid sulphate soils. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, pp391-402. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Van der Maesen, L.(2000). *Climate and Forests And the Kyoto Protocol.* Draft paper Friends of the Earth Australia. Native Forest Network Southern Hemisphere. *On-line publication:* http://www.nfn.org.au/climfor/index.html

Van Mensvoort, M.E.F and Le Quang Tri.(1988). Morphology and genesis of actual acid sulphate soils without jarosite in the Ha Tien Plain, Mekong Delta, Viet Nam. In: H. Dost (editor): *Selected papers of the Dakar Symposium on Acid Sulphate Soils*, pp11-15, International Institute for Land Reclamation and Improvement Publication No 44, Wageningen.

Van Wijk, A.L.M., Putr Gedjer Widjaja-Adhi, I., Ritsema, C.J and Konsten, C.J.M.(1993). A simulation model for acid sulphate soils, II: validation and application for water management strategies. In: D.L. Dent and M.E.F. van Mensvoort (eds.): *Selected Papers of the Ho Chi Minh City Symposium on Acid Sulphate Soils*, pp.341-356. International Institute for Land Reclamation and Improvement Publication No. 53, Wageningen.

Vaughan, D.J and Lennie, A.R.(1991).The iron sulphide minerals: their chemistry and role in nature. *Science Progress*, 75: p371-388.

Velders, G.(1997). Scientists and Policy makers. Change, Research and Policy, in *Newsletter on Global Change from the Netherlands*, 39, RIVM/NRP, Bilthoven.

Vieux, B.E., Bralts, V.F and Segerlind, L.J.(1988). Finite element analysis of response areas using geographic information systems. *Modelling Agricultural, Forest and Rangeland Hydrology*, ASAE Publication 07-88, St. Joseph, MI: American Society of Agricultural Engineers, pp.437-446.

Voigt, T., Bailey, M and Abramson, M.(1998). Air pollution in the Latrobe Valley and its impact upon resoiratory morbidity. *Australian and New Zealand Journal of Public Health,* Vol. 22. No.5. pp 556-561.

Wahba, G.(1990). Spline Models for Observed Data. CBMS-NSF Regional *Conference Series in Applied Mathematics* 59, SIAM, Philadelphia, Pennsylvania.

Wahba, G and Wendelberger, J.(1980). Some new mathematical methods for variational objective analysis using splines and cross validation. *Monthly Weather Review* 108: 122-1143.

Waite, T.D., Desmier, R., Melville, M and Macdonald, B.C.T.(2003). Permeable reactive barrier options for the management of acid sulfate soils drainage. In: *Groundwater Remediation of Trace Metals, Radionuclides and Nutrients, with Permeable Reactive Barriers*, (Eds) Naftz, D.L., Morrison, S.J., Davis, J.A. and Fuller, C.C. Academic Press, Chapter 3, pp 67-104.

Walker, P.H.(1972). Seasonal and stratigraphic controls in coastal floodplain soils. *Australian Journal of Soil Research,* 10: 127-142.

Walker, G.T.(1924): Correlations in seasonal variations of weather. I. A further study of world weather. *Mem. Indian Meteorol.* Dep. 24, 275-332.

Wang, W., Kleeman, R., Smith, N and Tseitkin, F.(2000). Seasonal predictions with a coupled global ocean-atmosphere model. *BMRC Research Report* No 77. On-line publication. http://www.bom.gov.au/bmrc/

Wang, X.L and Ropelewski, C.F.(1995). An assessment of ENSO-scale secular variability. *Journal of Climate,* 8, 1584-1599

Warwick, J.J and Haness, S.J.(1994). Efficacy of ARC/INFO GIS application to hydrologic modeling. *Journal of Water Resources Planning and Management*, 120(3):366-381.

WBM Oceanics, Australia.(1997). *Estuary Management Plan.* Cudgen, Cudgen and Mooball Creeks. Report to Tweed Shire Council.

WBM Oceanics, Australia.(1980). *Cabarita Gardens canal development tidal and flooding hydraulics*. Report prepared for Hansen Development Pty Ltd.

WBM Oceanics, Australia.(1998). *Cudgen Nature Reserve-Cudgen Lake Management Study*. Report prepared for NPWS.

Wendelaar Bonga, S.E and Dederen, L.H.(1986). Effects of acidified water on fish. *Endeavour*. New Series.10: 198-202.

White, I., Melville, M.D., Wilson, B.P., Price, C.B and Willett, I.R.(1993). Understanding acid sulfate in canelands. In: Bush, R.T. (ed), *Proceedings of* *the National Conference on Acid Sulfate Soils,* Coolangatta, 24-25 June, 1993, pp. 130-148. NSW Agriculture, Wollongbar.

White, I and Melville, M.D.(nd).*Restoring Lake Cudgen.* A community-based Coastal Environment Clean-up Project. A proposal to the Tweed Total Catchment Management Committee.

White, I and Melville, M.D.(1993). Treatment and containment of potential acid sulphate soils formation, distribution, properties and management of potential acid sulphate soils. CSIRO Centre for Environmental Mechanics, *Technical Report* No 53, Nov 1993, Canberra pp 103.

White, I., Melville, M.D., Lin, C., vanOploo, P and Wilson, B.P.(1995).Fixing problems caused by acid sulphate estuarine soils. In: Copeland, C. (Ed.) *Ecosystem Management: the Legacy of Science.* Halstead Press, Sydney.

White, I., Melville, M.D., Wilson, B.J and Sammut, J.(1997). Reducing acidic discharges from coastal wetlands in eastern Australia. *Wetlands Ecology and Management,* 5: 55-72.

White, I and Melville, M.D.(1996). Acid Sulphate Soils. Facing the Challenges. *Earth Foundation Australia, Monograph* 1, ISBN 0 9586983 0 9.

White, I., Heath, L and Melville, M.D.(1999a). Ecological Impacts of Flood mitigation and Drainage in Coastal Lowlands. *Australian Journal of Emergency Management,* Vol 14, No 3 .pp9-15.

White, I., Falkland, T and Scott, D.(1999b). Droughts in Small Coral Islands: Case Study, South Tarawa, Kiribati. *IHP-IV Project International Hydrological Programme*, UNESCO, Paris.

White, I.(2001a). Safeguarding Environmental Conditions for Oyster Cultivation in New South Wales. *Report for the NSW Healthy River Commission.* Centre for Resource and Environmental Studies, Australian National University, Canberra.

White, I.(2001b). Equilibrium Moisture Profiles in Consolidating, Sulfidic Clay Soils, In *Heat and Mass Transfer in the Natural Environment*, (Eds) Smiles.D.E, Raats,P.A.C and Warrick, A. AGU Monograph, Washington, D.C., USA. In Press.

White, I., Macdonald, B.C.T and Melville, M.D.(2001a). Modelling Shallow Groundwater in Soft, Sulfidic, Coastal Sediments. *Congress on Modelling and Simulation, MODSIM 2001,* Australian National University, Canberra, 10-13 December 2001. Vol 2 .(Eds): Ghassemi, F., Whetton, P., Little, R and Littleboy, M. pp567-572.

White, I., Smiles, D.E., Santomartino, S., van Oploo, P., MacDonald, B.C.T and Waite T.D.(2001b). Dewatering and the Hydraulic Properties of Soft, Sulfidic Coastal Clay Soils. *Water Resources Research* (Submitted)

Wigmosta, M.S., Vail, L.W and Lettenmaier, D.P.(1994). A distributed hydrology-vegetation model for complex terrain. *Water Resources Research,* 30: 1665-1679.

Willett, I.R., Crockford, R.H and Milnes, A.R.(1992). Transformation of iron, manganese and aluminium during oxidation of a sulphidic material from acid sulphate soil. In: Skinnr, H.C.W. and Fitzpatrick, R.W.(eds), *Biomineralization Processes of Iron and Maganese-Modern and Ancient Environments*, pp. 287-301. Cremlingen-Destedt., Germany: Catena Verlag.

Wilson, B.P.(1995). Soil and hydrological relations to drainage from sugarcane on acid sulphate soils. Unpublished PhD Thesis, School of Geography, UNSW.

Wilson, B.P., White, I., Melville, M.D.(1999). Floodplain hydrology, acid discharge and change in water quality associated with drained acid sulfate soil. *Marine and Freshwater Research,* 50, 149-157.

Wilson, S.P and Hyne, R.V.(1997). Toxicity of acid-sulfate soil leachate and aluminium to embryos of the Sydney rock oyster. *Ecotoxicology and Environmental Safety,* 37: 30-36.

Wilson, J., Evans, P and Kelleher, N.(2002). Fish Kills in Cockrone Lagoon- Implications for Entrance opening of Coastal Lakes. *Proceedings of Coast to Coast. Source to sea, Australia's National Coastal Conference*. Tweed Heads, Australia, pp101-104.

Wolfe, M.L and Neale, C.M.U.(1988). Input Data Development for a Distributed Parameter Hydrologic Model (FESHM), *Proceedings in Modeling Agricultural, Forest and Rangeland Hydrology, International Symposium,* ASAE, Chicago, Illinois, pp. 462-463.

Woodroffe, C.D and Chappell, J.(1991). Application of Holocene studies to conservation: The case of low-energy coasts. In: Brierly, G and Chappell, J (eds). *Applied Quarternary Studies*, 75-88. Australian National University, Canberra.

Woodhead, A.(1999). Benchmarking Acid Sulfate Soils. *ASSMAC Report, NSW Department of Agriculture.*

Woodhead, A.(2003). Acid Sulfate Soils 4 Years On- What Changed? *NSW Agriculture and ASSMAC publication.* ISBN 0 7347 1525 0

WTTC.(1999). *Travel and Tourism's Economic Impact.* World Trade and Tourism Council, London, UK.

Yang, X.(1997). Applications of Remote Sensing and GIS to Acid Drainage Management in an Estuary Floodplain Agricultural Environment. Unpublished PhD Thesis, University of New South Wales.

Yang, X., Zhou, Q and Melville, M.(1999). An integrated drainage network analysis system for agricultural drainage management part 2: the application. *Agricultural Water Management,* 1517: 1-14.

Yin, T.P and Chin, P.Y.(1982). Effects of water table management on performance of oil palm on acid sulfate soils in Penisular Malaysia. In: H.Dost and N.Van Breemen (eds). *Proceedings of the Bangkok Symposium on Acid Sulfate Soils,* 260-271. International Institute for Land Reclamation and Improvement Publication No 31, Wageningen.

Yoon, J.(1996). Watershed-Scale Nonpoint Source Pollution Modeling and Decision Support System Based on a Model-GIS-RDBMS Linkage. *American Water Resources Association Symposium on GIS and Water Resources* Sept 22-26, Lauderdale, FL. On line publication: http://www.awra.org/proceedings/gis32/jyoon/

Young, Y., Onstad, C., Bosch, D and Anderson, W.(1989). AGNPS, A non-point source pollution model for evaluating agricultural watersheds. *Journal of Soil and Water Conservation*, 44, 168-173.

Youngs, E.G and Towner, G.D.(1970). Comments on 'Hydrodynamics in swelling soils' by Philip, J.R, *Water Resources Research*, 6, 1246-1247.

Zhang, Y., Wallace, J.M and Battisti, D.S.(1997). ENSO-like Interdecadal Variability: 1900-1993. *Journal of Climate*, 10, 1004-1020.

Zhang, L., Dawes, W.R and Walker, G.R.(2001). Response of mean annual evapotranspiration to vegetation at catchment scale. *Water Resources Research*, Vol 37, No 3, 701-708.

Zhang, L., Dawes, W.R and Walker, G.R.(1999). Predicting the effect of vegetation changes on catchment average water balance, *Technical Report 99/12*. Cooperative Research Centre for Catchment Hydrology, Canberra, ACT.

Ziemkiewicz, P., Skousen, J and Lovett, R.(1995). Open limestone channels for treating acid mine drainage: A new look at an old idea. Chapter 25 *of "Acid mine drainage control and treatment*":Compiled by Skousen, J. G. and Ziemkiewicz, P. F. West Virginia University and the National Mine Land Reclamation Center, Morgantown, West Virginia. pp 225-230.

Appendix A List of Rainfall Stations Used in This Thesis

id	long	lat	elevation	name	start	finish
058213	153.2344	-28.2611	425	NUMINBAH GATE	1998	
058212	153.3964	-29.1830	63	EVANS HEAD RAAF BOMBING RANGE	1973	1979
058211	153.2853	-29.3681	5	WOOMBAH (ADAMS STREET)	1965	1968
058210	153.3347	-28.5041	280	COMMISSIONERS CREEK (BLUE RIDGE)	1949	1985
058209	153.5605	-28.4025	5	POTTSVILLE (CARNARVON COURT)	1976	1980
058208	153.0520	-28.8775	21	CASINO AIRPORT AWS	1998	
058207	152.8069	-29.0417	100	BUSBY FLAT	1972	
058206	153.3611	-28.7228	25	EWING BRIDGE CORNDALE (COOPERS CK)	1991	
058204	153.3467	-28.3217	30	BOAT HARBOUR (ROUS RIVER)	1968	1972
058202	153.0758	-28.7400	40	BENTLEY (BACK CREEK)	1993	
058201	153.2386	-28.7967	10	TUNCESTER (LEYCESTER CREEK)	1948	
058199	153.1756	-28.7492	20	ROCK VALLEY (LEYCESTER CREEK)	1996	
058198	153.5585	-28.8353	1	BALLINA AIRPORT AWS		
058197	153.2386	-28.2694	320	MOUNT NUMINBAH	1990	
058195	152.9653	-28.5078	100	WIANGAREE POST OFFICE	1986	
058194	152.7136	-28.3842	240	DAIRY FLAT	1986	
058193	153.3000	-28.3500	20	EUNGELLA (OXLEY RIVER BRIDGE)	1973	1976
058192	152.8806	-28.9883	70	UPPER MONGOGARIE (MARANGAROO)	1985	
058186	153.4000	-28.3283	3	MURWILLUMBAH (TWEED RIVER)	1971	1973
058185	152.6333	-29.4633	20	HEIFER STATION (CLARENCE RIVER)	1968	
058183	153.3059	-28.5013	100	DOON DOON (DOUGHBOY MOUNTAIN)	1980	
058182	153.3410	-28.5063	240	DOON DOON (UPPER COMMISSIONERS CRK)	1980	1994
058180	153.2133	-28.6083	60	NIMBIN (GOOLMANGAR CREEK)	1985	
058171	153.4139	-28.9311	14	MEERSCHAUM VALE (JENBETDAPH)	1977	
058166	153.2167	-29.4000	3	WARREGAH ISLAND	1975	1989
058165	153.4090	-28.6217	140	ROSEBANK (UPPER COOPERS CREEK)	1975	
058164	153.4500	-29.1333	31	EVANS HEAD (ANSON AVENUE)	1980	
058163	153.4667	-28.2167	140	TERRANORA	1935	
058162	153.4583	-28.7278	30	NASHUA (WILSONS RIVER)	1993	
058160	153.2667	-28.8333	9	LISMORE LIGHTNING	1928	
058158	153.3784	-28.3408	18	MURWILLUMBAH (BRAY PARK)	1972	
058157	153.0500	-29.0000	38	ELLANGOWAN (EAGLEHAWK)	1972	1980
058156	153.1650	-28.3433	135	TYALGUM (WARNING VIEW)	1971	
058154	153.0500	-28.9667	38	ELLANGOWAN (YORKLEA ROAD)	2000	
058153	153.4333	-28.2333	37	CAROOL (STITZS)	1992	1998
058151	152.8500	-28.7500	152	DYRAABA CREEK (TUBUMOREY)	2000	
058150	153.3200	-28.2583	91	UPPER CRYSTAL CREEK (ARKUNA)	1970	1999
058149	153.3526	-29.4053	3	ILUKA (OWEN ST)	1970	
058148	153.1519	-28.5276	345	LILLIAN ROCK (WILLIAMS ROAD)	1963	
058147	153.2783	-28.6725	35	THE CHANNON	1926	
058146	152.9964	-28.6217	55	KYOGLE (LARKIN STREET)	1970	
058144	152.8000	-29.0500	100	RAPPVILLE (BUSBY FLAT)	1969	1976
058141	152.9817	-28.4133	160	LOADSTONE (HIGH VIEW)	1969	
058140	152.9650	-28.5083	80	WIANGAREE BRIDGE (RICHMOND RIVER)	1972	1974
058139	152.8958	-28.5917	130	EDEN CREEK (KARINGAL)	1969	1997
058137	153.5800	-28.2583	3	KINGSCLIFF (MARINE PARADE)	1969	
058136	153.5167	-28.9000	31	PIMLICO (AMAROO)	1968	1979
058135	153.4467	-28.8944	32	MEERSCHAUMVALE (MEERSCHAUM VALE)	1968	
058134	152.7667	-28.7667	366	THERESA CREEK (ROSEVIEW)	1968	1976
058133	153.3617	-28.7183	37	CORNDALE (WILLOW VALE)	1938	
058132	152.8667	-28.7167	91	DYRAABA CENTRAL	1967	1977
058131	153.4550	-28.8542	140	ALSTONVILLE TROPICAL FRUIT RESEARCH	1963	
058129	153.2632	-28.4660	61	KUNGHUR (THE JUNCTION)	1966	
058127	153.4050	-28.7322	110	CLUNES (MAIN RD)	1962	
058126	152.7667	-28.5833	201	CLUNES (TOONUMBAR)	1965	1971
058125	153.2870	-28.5470	810	NIMBIN (MOUNT NARDI)	1965	1996
058124	153.0670	-29.1330	31	MAIN CAMP	1965	1974
058123	153.3167	-28.2833	61	UPPER CRYSTAL CREEK	1979	1988
058122	152.7460	-28.4213	202	UNUMGAR STATE FOREST	1965	1972
058121	152.9500	-28.8000	34	STRATHEDEN	1965	1974
058120	153.1830	-28.7500	30	ROCK VALLEY POST OFFICE RESIDENCE	1965	1972
058119	152.9000	-28.8500	70	PIORA	1965	1974
058118	153.3170	-28.4000	180	MOUNT WARNING	1965	1973
058116	153.0000	-28.4500	110	LYNCHS CREEK (WARRAZAMBLE ROAD)	1965	1980

058115	152.8778	-28.3867	145	GREVILLIA (LINDESAY VIEW)	1965	
058114	153.3670	-28.5530	220	MULLUMBIMBY (HUON BROOK)	1965	1977
058113	153.0862	-28.4785	170	GREEN PIGEON (MORNING VIEW)	1965	
058110	152.9667	-28.3500	168	COUGAL	1960	
058109	153.1720	-28.3670	83	TYALGUM (PUMPENBIL)	1965	
058108	153.0330	-28.7670	49	BACKMEDE (GREEN GATES)	1965	1976
058107	153.4833	-28.4500	15	BURRINGBAR (HARNETT)	1965	1978
058106	153.0900	-28.6040	225	CAWONGLA	1965	
058105	153.1000	-29.2333	55	GIBBERAGEE	1991	
058103	153.5458	-28.5522	5	BRUNSWICK HEADS BOWLING CLUB	1890	
058100	152.8167	-29.3667	91	ROSEBANK	1964	1974
058099	152.9881	-29.2839	50	WHIPORIE POST OFFICE	1964	
058097	153.2783	-29.1525	22	NEW ITALY	1997	
058090	152.9140	-28.4812	80	ROSEBERRY	1997	
058088	152.8967	-28.6706	82	ETTRICK (TOPNORI)	1965	
058087	153.5000	-28.7000	60	PEARCES CREEK	1911	1935
058081	152.8167	-28.9667	100	UPPER MONGOGARIE (KIMBERLEY)	1963	1985
058078	153.1122	-28.7789	29	BENTLEY	1964	
058073	152.7933	-29.4964	80	COPMANHURST (STOCKYARD CREEK)	1957	
058072	153.4542	-28.6533	175	FEDERAL POST OFFICE	1904	1998
058071	153.3170	-28.8220	170	LISMORE (GOONELLEBAH)	1962	1977
058070	153.4122	-28.6400	75	ROSEBANK (REPENTANCE CREEK)	1957	
058067	153.3760	-28.2430	330	TOMEWIN COMPOSITE WAS 058152	1913	
058065	153.4330	-29.0170	6	BROADWATER SUGAR MILL	1915	1975
058063	153.0493	-28.8755	26	CASINO AIRPORT	1858	
058061	153.3449	-29.0713	5	WOODBURN POST OFFICE	1886	
058060	153.3783	-28.5988	381	WHIAN WHIAN (RUMMERY PARK)	1943	
058058	153.3333	-28.4167	28	UKI (SUNNYVALE)	1922	1972
058057	153.2078	-28.3600	55	TYALGUM (COODGEE STREET)	1950	1992
058056	153.5489	-28.2044	5	TWEED HEADS GOLF CLUB	1886	
058054	153.1422	-28.3644	140	PUMPENBIL (TYALGUM)	1990	
058053	153.1500	-28.9333	17	TATHAM	1939	1969
058052	153.2670	-29.2000	18	TABBIMOBILE STATE FOREST	1946	1971
058050	152.9167	-28.4833	152	ROSEBERRY STATE FOREST NURSERY	1940	1968
058044	153.2233	-28.5966	70	NIMBIN POST OFFICE	1903	
058042	153.4000	-28.3167	6	MURWILLUMBAH POST OFFICE	1890	1973
058040	153.4948	-28.5451	15	MULLUMBIMBY (FAIRVIEW FARM)	1898	
058039	152.7080	-29.0370	175	MOUNT PIKAPENE FORESTRY	1940	1995
058038	153.1994	-29.4536	6	MACLEAN (MCLACHLAN STREET)	1889	
058037	153.2617	-28.8092	11	LISMORE (CENTRE STREET)	1884	
058036	153.2217	-28.3106	100	MURWILLUMBAH (LIMPINWOOD)	1928	
058035	153.1580	-28.5320	300	LILLIAN ROCK	1928	1959
058033	153.1041	-29.4967	8	LAWRENCE POST OFFICE	1884	
058032	153.0036	-28.6225	80	KYOGLE POST OFFICE	1905	
058031	153.2530	-28.4710	61	KUNGHUR POST OFFICE	1950	1970
058030	152.8667	-29.1333	60	RAPPVILLE (KIPPENDUFF)	1930	1976
058027	153.2500	-29.4330	2	HARWOOD SUGAR MILL	1915	
058026	152.8296	-28.4414	140	GREVILLIA (SUMMERLAND WAY)	1952	2000
058023	153.3958	-28.7908	120	MCLEANS RIDGES (LASCOTT DRIVE)	1952	
058022	152.8167	-28.7500	46	DYRAABA CREEK	1939	1968
058020	153.3642	-28.2903	20	MURWILLUMBAH (TALESWOOD)	1950	
058019	153.3139	-28.5328	230	DOON DOON (MCCABES ROAD)	1952	
058018	153.5181	-28.8408	30	CUMBALUM (FAIRVIEW)	1884	1985
058016	152.7549	-28.4244	195	UNUMGAR(SUMMERLAND WAY)	1971	1973
058015	153.2867	-28.9889	6	CORAKI POST OFFICE	1895	
058013	153.4333	-28.3167	5	CONDONG SUGAR MILL	1887	1972
058012	153.3633	-29.4333	29	YAMBA PILOT STATION	1877	
058011	153.2750	-28.3125	35	CHILLINGHAM	1950	
058010	152.6000	-28.4500	400	CASTILLE	1933	1970
058009	153.6347	-28.6408	95	BYRON BAY (CAPE BYRON LIGHTHOUSE)	1948	
058007	153.6144	-28.6517	10	BYRON BAY (JACARANDA DRIVE)	1892	
058005	153.1933	-28.3944	90	BRAYS CREEK (MISTY MOUNTAIN)	1950	
058004	152.7658	-28.7872	195	MUMMULGUM (BINGEEBEEBRA)	1936	
058002	153.5333	-28.6833	46	BANGALOW MOTEL	1900	1975
058001	153.5698	-28.8528	3	BALLINA (CROWLEY VILLAGE)	1892	
058000	153.4500	-28.8500	160	ALSTONVILLE POST OFFICE	1903	1973
057127	152.5883	-28.9889	150	TABULAM (CLARENCE WAY)	1991	

057121	152.7089	-28.9761	215 MALLANGANEE (HEREFORD HILLS)	1987	
057120	152.7200	-29.1961	270 BARYULGIL (MOOKIMA)	1987	1997
057114	152.5950	-29.1967	79 BARYULGIL (CLARENCE RIVER)	1993	
057099	152.2333	-29.1833	355 TENTERFIELD (BILLARIMBA)	1964	1978
057098	152.5667	-29.0167	140 ALICE (CLEVELAND)	1997	
057097	152.5833	-29.0333	101 ALICE (TILBAROO)	1999	
057096	152.4260	-28.7470	510 PRETTY GULLY (LANIKAI) WAS 058079	1963	1971
057095	152.4500	-28.7569	555 TABULAM (MUIRNE)	1970	
057090	152.4833	-29.4667	90 CANGAI (HANGING ROCK)	1969	1975
057089	152.6150	-29.3467	170 FINE FLOWER CREEK (WAVE HILL)	1969	1988
057085	152.6017	-28.5908	210 OLD BONALBO (WIWIYAMBA)	1910	
057080	152.7333	-28.9000	220 MALLANGANEE T.Q. GATE	1965	1975
057078	152.7000	-28.5333	274 BONALBO OLD (GLEN HUON HMSD)	1995	
057077	152.5680	-29.2210	100 BARYULGIL (YUGILBAR)	1964	1979
057074	152.4117	-28.6150	335 URBENVILLE (CALDERWOOD GLEN)	1964	1994
057066	152.5178	-29.3467	85 COOMBADJHA (CARNHAM)	1964	
057064	152.6500	-29.0667	137 TABULAM (KEEMBIN)	1972	1976
057051	152.5917	-29.1917	85 BARYULGIL (MOUNTAIN VIEW)	1961	
057031	152.4120	-28.3330	1036 ACACIA PLATEAU (BELMONT)	1954	1970
057027	152.6830	-28.8170	188 TUNGLEBUNG (Xnm WINGFIELD)	1952	1971
057026	152.5034	-28.2846	565 OLD KOREELAH (WHITE SWAMP (EDENDALE 2	1894	
057024	152.6069	-28.3897	395 WOODENBONG (UNUMGAR ST)	1933	
057021	152.5500	-28.4670	366 URBENVILLE STATE FOREST	1938	1968
057020	152.5481	-28.4736	370 URBENVILLE POST OFFICE	1935	
057019	152.7250	-28.9083	185 MALLANGANEE (SANDILANDS ST)	1972	1973
057018	152.5665	-28.8914	130 TABULAM POST OFFICE	1887	
057015	152.5942	-28.6556	190 OLD BONALBO POST OFFICE	1915	
057009	152.3000	-28.9000	671 GIRARD STATE FOREST	1934	1968
057006	152.4500	-29.4670	100 DUMPE	1920	1971
057005	152.3745	-28.9274	495 DRAKE GENERAL STORE	1891	
057003	152.6226	-28.7367	170 BONALBO POST OFFICE	1913	
056239	152.0974	-28.7014	965 WILSONS DOWNFALL	1992	
056231	152.3067	-28.4083	574 LEGUME POST OFFICE	1954	1992
056215	152.1000	-28.8833	945 BOONOO BOONOO POST OFFICE	1992	
056212	152.2533	-28.8433	585 TENTERFIELD (SANDY HILL (BOOROOK))	1970	
056211	152.2533	-28.9100	560 SANDY HILL (TOURELLO PK.)	1964	
056208	152.1333	-28.4833	678 CULLENDORE (BORDER)	1970	1980
056203	152.1333	-29.0472	865 BLACK SWAMP (ATHLYNE)	1970	
056202	152.1552	-28.9777	820 BLACK SWAMP (MAXWELL)	1970	
056061	152.0670	-28.6670	940 LISTON POST OFFICE	1960	1976
056059	152.1000	-29.0500	850 TENTERFIELD (COOREDULLA)	1958	1969
056054	152.0333	-29.5000	1100 DEEPWATER (GLEN GOWRIE)	1962	1975
056040	152.0980	-28.4790	820 CULLENDORE (MERRIGAL)	1949	
056038	152.1600	-28.5550	675 WYLIE CREEK (ALOOMBA)	1914	
056032	152.0212	-29.0649	870 TENTERFIELD (WOOD ST)	1870	
056027	152.2511	-28.6433	270 RIVERTREE (MYALL)	1893	1991
056023	152.4157	-28.3933	420 OLD KOREELAH (MCPHERSON)	1912	
056022	152.3506	-28.4622	385 LEGUME (NEW KOREELAH)	1903	
041542	152.1442	-28.3342	500 BENCHMARK	1991	
041539	152.1983	-28.3817	550 WESTMORE	1995	
041525	152.1003	-28.2061	475 WARWICK	1997	
041516	152.0167	-28.0333	471 ALLORA TM	1969	1972
041465	152.0900	-28.4283	670 CHERRABAH	1983	
041464	152.3300	-28.1553	600 OAKINGTON	1977	
041456	152.3767	-28.0533	732 CUNNINGHAMS GAP NATIONAL PARK	1976	
041444	152.3330	-28.3330	560 KILLARNEY (LONG CROSSING)	1924	1965
041438	152.0067	-28.3619	540 SILVERWOOD DAM	1974	
041335	152.4170	-28.2170	660 EMU VALE (GUMBUBAL)	1959	1968
041334	152.0750	-28.3633	683 ROKEBY	1959	
041332	152.3500	-28.0667	640 AKUNA	1959	1963
041323	152.2633	-28.0317	549 MANDALA FARM	1959	
041322	152.2830	-28.2830	649 TANNYMOREL (BEVERLY HILLS)	1959	1969
041294	152.0080	-28.5170	853 DALVEEN (EAST LYNNE)	1959	1970
041279	152.3000	-28.1667	549 GLENMORE	1959	1975
041276	152.1500	-27.9167	604 GLENRIVE	1959	
041274	152.1142	-28.3144	482 GLENRAE	1959	
041267	152.1333	-27.8500	585 HILLVIEW	1959	1974

041262	152.3333	-28.1500	600 KEWARRA	1959	1975
041259	152.1292	-28.0717	500 CLINTONVALE	1959	
041253	152.0333	-27.9500	533 OAKDENE	1959	1974
041238	152.1000	-28.4333	597 MYRTLE GROVE	1990	1991
041234	152.2067	-28.3133	494 LOCH LOMOND	1958	1992
041233	152.1500	-28.4000	485 ELBOW VALLEY POST OFFICE	1959	1969
041229	152.2622	-28.0775	543 MARYVALE	1967	
041228	152.1500	-28.0333	543 MELMERE	1966	1969
041227	152.0320	-28.1230	480 WARWICK (WILLOWVALE)	1959	1983
041226	152.0000	-27.9000	511 MILLVALE	1959	1991
041225	152.0500	-27.8333	506 MIRRA BOOKA	1959	
041216	152.0519	-28.0333	495 RIVERSIDE	1959	
041208	152.3472	-28.3592	610 SPRING CREEK	1959	
041207	152.2833	-28.2333	579 SPRINGDALE	1959	1973
041185	152.1167	-28.1500	524 WESTHALL	1959	1975
041176	152.0258	-28.2247	477 WARWICK DRAGON ST	1967	1994
041167	152.2833	-28.1667	549 HELENVALE	1919	
041165	152.4200	-28.2950	579 BONNIE BRAE	1913	1991
041134	152.4170	-28.2830	641 SPRING CREEK (TOP PLAINS)	1952	
041120	152.2064	-28.1897	520 YANGAN POST OFFICE	1912	
041111	152.0333	-28.2167	453 WARWICK POST OFFICE	1865	1985
041107	152.1200	-27.9183	549 UPPER PILTON	1933	
041106	152.1000	-28.0000	580 FOREST SPRINGS UPPER	1927	
041098	152.2425	-28.2858	517 TANNYMOREL	1916	
041085	152.3942	-28.3253	884 QUEEN MARY FALLS	1959	
041067	152.2670	-28.0500	525 MARYVALE (BLAKEFIELD)	1913	1979
041057	152.3000	-28.3330	550 KILLARNEY POLICE STATION	1938	1973
041056	152.2958	-28.3322	514 KILLARNEY POST OFFICE	1889	
041046	152.4161	-28.2836	700 THE HEAD	1958	
041044	152.1003	-28.2061	475 HERMITAGE	1898	2000
041032	152.2000	-28.1000	500 GLADFIELD (MYRA)	1909	
041031	152.0167	-27.4000	442 GEHAM STATE SCHOOL	1912	1974
041028	152.2500	-28.2267	503 EMU CREEK	1893	
041013	152.0661	-28.2264	456 CANNING DOWNS	1897	
041004	152.0539	-28.2675	500 ALBION	1995	
040921	152.3864	-27.0239	95 BRAEMORE	2000	
040920	152.7697	-27.6267	50 EASTERN HEIGHTS	2000	
040918	153.0761	-27.3083	10 BRIGHTON BOWLS CLUB	1997	
040916	153.1706	-27.3800	3 FISHERMAN ISLANDS RAIL	1969	1970
040914	152.4975	-27.4944	70 MT TARAMPA	1993	
040913	153.0389	-27.4806	8 BRISBANE	1987	
040911	153.0150	-27.4558	150 HILLTOP GARDENS	1990	
040899	153.3800	-28.2300	300 TALLOWOOD	1972	1975
040895	152.9150	-27.4150	80 FERNY GROVE TM	1995	
040890	152.9858	-27.5242	11 GRACEVILLE COLEMAN ST	1995	
040888	153.3433	-27.4967	10 PEEL ISLAND NATIONAL PARK	1986	
040884	153.2608	-27.9244	50 GUANABA BIRDS RD	1997	
040883	152.0575	-27.6847	400 DEVERTON SAWPIT GULLY RD	1994	
040864	153.3517	-28.0167	50 CARRARA BRADSTONE RD	1970	1975
040863	153.2739	-27.7914	20 NORWELL EGGERSDORF RD	1997	
040862	153.1583	-27.5864	66 BURBANK LEACROFT ROAD	1969	1970
040860	152.1786	-27.2022	340 ANDURAMBA DIP	1912	1974
040854	153.1958	-27.6836	10 LOGAN CITY WATER TREATMENT	1997	
040853	153.2953	-27.6022	15 REDLAND BAY GOLF CLUB	1977	1996
040852	153.1794	-28.0272	120 CANUNGRA LAND WARFARE CENTRE	1992	
040851	153.3772	-27.6294	10 LAMB ISLAND PINE AVE	1974	1974
040849	153.3656	-27.9142	30 COOMBABAH WATER TREAT	1946	
040842	153.1292	-27.3917	4 BRISBANE AERO	1893	
040808	152.1961	-27.2644	400 CRESSBROOK DAM	1990	
040807	153.1017	-27.2583	15 BRAMBLE BAY BOWLING CLUB	1945	
040798	153.0722	-27.5153	50 COORPAROO BCC	1967	1969
040793	152.8367	-27.7633	150 THE GAP ALERT	1996	
040775	153.1264	-27.6128	100 SPRINGWOOD DORSET DR	1981	
040774	152.9500	-27.1000	20 MORAYFIELD	1989	2000
040771	153.1833	-27.7167	17 BEENLEIGH LEHMAN RD	1991	
040770	153.2492	-27.5156	15 ORMISTON COLLEGE	1988	
040768	153.0170	-27.8670	60 JIMBOOMBA (MILLSTREAM ROAD)	1988	

040767	153.0320	-27.4980	30 BRISBANE (P.A.HOSPITAL)	1988	
040766	153.0910	-27.7750	20 BEENLEIGH (LOGAN VILLAGE)	1987	
040764	153.4283	-27.9389	3 GOLD COAST SEAWAY	1999	
040763	152.6000	-27.3997	78 WIVENHOE DAM	1999	
040760	153.0883	-27.7617	50 LOGAN VILLAGE	1993	
040751	152.3753	-27.7956	200 THORNTON	1971	1972
040744	152.3744	-27.0897	99 TOOGOOLAWAH BVRT	1997	
040732	153.4186	-27.5308	70 WALLEN WALLEN	1985	
040725	152.9883	-28.1683	150 CHRISTMAS CREEK RD	1984	
040724	153.4250	-28.0497	4 MERMAID WATERS TIMANA AV	1984	1995
040718	152.9000	-27.5000	90 BROOKFIELD (PENDALE)	1983	1989
040717	153.5040	-28.1650	6 COOLANGATTA AIRPORT AWS	1982	
040715	153.1933	-27.6511	20 SHAILER PARK OREGON DRVE	1980	
040704	153.1000	-27.6830	20 BEENLEIGH (MARSDEN)	1982	
040703	152.9150	-27.4150	80 FERNY GROVE CEDAR CK RD	1964	1994
040702	152.5322	-27.7617	60 STOKES CROSSING	1994	
040700	153.2650	-28.2300	920 SPRINGBROOK (QUOLL HOUSE)	1979	1991
040697	153.1014	-27.2450	25 REDCLIFFE COUNCIL	1981	
040693	152.8161	-27.3789	177 HIGHVALE	1954	
040691	153.3167	-28.1167	64 QUINDREX MUDGEERABA	1989	
040689	153.1760	-27.3638	2 BISHOP ISLAND	1993	
040685	153.1670	-27.0500	2 BRIBIE ISLAND Q'LD UNIVERSITY	1978	1993
040683	152.4833	-27.1167	53 LOWER CRESSBROOK	1991	
040677	152.6556	-28.1806	190 MAROON DAM	1971	
040676	152.8383	-28.0833	100 KOORALBYN AIRSTRIP	1997	
040675	152.3890	-27.9100	240 LAIDLEY (TOWNSON)	1977	
040673	152.9500	-27.5333	40 JINDALEE CLOVERDALE LAWN	1972	1973
040672	152.0239	-27.5486	300 TERRENE	1974	
040659	152.9408	-27.6958	50 GREENBANK THOMPSON ROAD	1975	
040637	152.7000	-27.0981	533 MOUNT MEE FOREST STATION	1970	
040634	153.3936	-28.2058	70 CURRUMBIN VALLEY	1992	
040633	152.9383	-27.3033	25 STRATHPINE COLONIAL DRIVE	1975	
040631	153.0790	-27.7538	17 CHAMBERS FLAT	1993	
040623	152.9917	-27.6911	40 GREENBANK ARMY CAMP	1974	1992
040620	153.2330	-28.2330	300 SPRINGBROOK (LENORE VALE)	1950	1968
040619	152.7333	-28.3167	180 RATHDOWNEY	1917	1973
040617	152.7250	-27.2420	150 DAYBORO (RAYNBIRD CREEK)	1953	1970
040614	152.7330	-28.3500	520 RATHDOWNEY (MOUNT LINDSAY)	1919	1972
040610	153.0872	-28.2522	250 HILLVIEW (DARLINGTON)	1975	
040609	153.4456	-28.1181	3 ELANORA WATER TREAT	1935	
040608	153.4008	-28.0039	6 BENOWA WATER TREAT	1974	1990
040607	153.2717	-28.2031	780 SPRINGBROOK ROAD	1966	1981
040606	153.3270	-28.1060	120 MUDGEERABA WATER TREATMENT	1974	
040605	152.2670	-27.7830	300 LAIDLEY (ROCK VIEW)	1919	1969
040602	153.3000	-28.0330	60 GILSTON STATE SCHOOL	1922	1968
040599	153.3830	-28.2000	180 CURRUMBIN (CAMBERRA)	1927	1973
040597	152.7330	-28.2000	350 BOONAH FOREST HOME	1921	1969
040591	152.6670	-28.0000	125 BOONAH (x RANGEVIEW)	1947	1970
040584	153.2878	-28.0483	110 HINZE DAM	1974	
040583	153.0742	-28.2714	240 WIDGEE	1929	
040580	152.4500	-27.5000	72 LOCKROSE	1991	
040578	152.8070	-27.2130	80 DAYBORO (ARMSTRONG CREEK)	1995	
040576	152.5000	-28.0000	150 RANGEVIEW FARM	1947	1970
040570	152.3569	-27.6964	125 MULGOWIE	1993	
040558	153.2344	-28.2156	225 GLENGAVEN	1991	
040554	152.9833	-27.6167	45 CLOVERDALE LAWNS	1992	
040550	153.2350	-28.2220	250 NATURAL BRIDGE (NUMINBAH)	1928	
040544	153.1189	-27.9075	28 BROMFLEET	1967	1968
040542	153.0150	-27.7881	3 MACLEANS BRIDGE	1959	
040538	153.0830	-27.9830	80 BEAUDESERT (TABRAGALBA)	1889	1993
040537	153.4081	-27.4961	20 DUNWICH	1960	
040536	152.8000	-27.1333	460 OCEAN VIEW	1956	
040535	153.0830	-28.1170	150 BEAUDESERT (CAINBABLE)	1929	1974
040534	153.2683	-28.1558	450 WUNBURRA	1953	
040533	152.9450	-27.4664	260 MT COOT-THA ABQ 2 BCC	1971	1995
040532	153.1614	-27.4247	20 WYNNUM BCC	1973	1997
040531	153.0508	-27.3317	20 BOONDALL BCC	1973	

040530	152.9883	-27.5853	10 INALA BCC	1973	
040529	153.1000	-27.5330	40 MOUNT GRAVATT EAST BCC	1971	1989
040527	153.0500	-27.6170	40 ACACIA RIDGE BCC	1973	1991
040524	153.2850	-28.1467	177 LITTLE NERANG DAM	1926	
040523	152.5360	-28.2638	630 BOONAH (BORDER GATE)	1958	
040517	152.7500	-27.1833	100 MCKENZIE CREEK	1953	
040516	153.3544	-27.8417	10 COOMERA FOXWELL ROAD	1992	1995
040515	152.2360	-28.0120	600 ALLORA (DAANDINE PASTORAL COMPANY)	1972	1977
040512	152.9856	-27.6542	40 FORESTDALE STAPYLTON RD	1973	
040497	152.8575	-27.9319	41 THE OVERFLOW	1944	
040495	153.0353	-27.4156	8 GYMPIE ROAD TM	1988	
040493	152.5350	-27.7797	80 HOMELEIGH	1912	
040490	152.5333	-28.2167	274 CARNEYS CREEK	1972	
040488	153.0175	-27.4208	30 GRANGE BOWLING CLUB	1972	
040487	153.2050	-28.2250	760 BEECHMONT (BINNA BURRA)	1954	1993
040485	152.5167	-28.2500	610 WILSONS PEAK	1919	
040484	153.4100	-27.8920	10 SOUTH STRADBROKE ISLAND (CURRIGEE)	1972	1997
040483	152.6670	-28.1830	200 BOONAH (POINTRO)	1922	1971
040480	152.1242	-27.2883	459 PERSERVERANCE DAM	1971	
040479	152.9830	-27.4330	60 ENOGGERA ARMY AREA	1972	1984
040476	152.9517	-27.4097	50 KEPERRA COUNTRY GOLF CLUB	1972	
040471	153.4083	-27.8333	1 COURAN COVE		
040468	153.0806	-27.4686	20 CANNON HILLS BOWLS CLUB	1972	
040463	152.9697	-27.5594	15 OXLEY ENGLEFIELD RD	1971	
040462	152.9167	-27.7500	60 CLOVER DOWNS	1999	
040461	152.9308	-27.3947	50 FERNY HILLS AUST WOOLSHED	1971	
040460	153.2381	-27.6081	70 MOUNT COTTON UNI FARM	1966	
040459	153.1000	-27.5000	20 CARINA BCC DONALDSON RD	1971	1989
040458	153.1825	-27.5314	30 CAPALABA WATER TREAT	1971	
040457	152.9042	-27.5767	23 WACOL DPI	1971	1980
040454	153.0000	-27.8330	40 JIMBOOMBA (GLENLOGAN FIELD STN)	1971	1982
040452	152.9222	-27.5469	68 MT OMMANEY GOLF CLUB	1971	1995
040450	153.0000	-27.5170	10 LONG POCKET LABORATORY CSIRO	1968	
040449	152.2017	-27.5769	130 PLACID HILLS	1970	
040447	152.4614	-27.9906	168 RHONDA	1953	
040439	153.2830	-28.2330	870 SPRINGBROOK (ALPINE PANORAMA)	1969	1981
040437	152.6500	-27.4500	70 RIVERMEAD	1971	
040436	152.3286	-27.5456	93 GATTON QDPI RESEARCH STN	1968	
040433	153.3667	-28.2333	140 GREEN VALLEY	1998	
040431	152.3330	-27.2500	220 ESK STATE FOREST R531	1969	1993
040429	153.1147	-27.5958	25 ROCHEDALE SOUTH	1969	
040425	152.8425	-27.2178	90 DAYBORO STRONG ROAD	1971	1975
040424	152.0814	-27.7550	330 WEST HALDON WAS 041123	1915	
040422	152.0167	-27.0500	305 EMU CREEK	1922	1976
040418	152.9220	-27.5280	40 MOGGILL VET.RESEARCH FARM	1968	1976
040417	153.4433	-28.0717	8 MIAMI BARDON AVE	1968	
040416	153.3242	-28.0000	3 CLEARVIEW TM	1994	
040413	153.0397	-28.1561	137 CENTRAL KERRY	1967	
040411	152.9061	-27.8481	40 ROMANI	1967	
040410	153.3333	-27.7833	2 JACOBS WELL	1967	1975
040409	152.8000	-27.9333	67 GLEN RETREAT	1967	1975
040408	153.2667	-27.7167	12 THE GEM HOTEL	1959	
040407	153.0328	-28.0558	90 LUMEAH	1931	
040406	153.2011	-27.7092	13 BEENLEIGH BOWLS CLUB	1967	
040404	152.8800	-28.2633	150 GLENAPP	1919	
040403	152.3500	-27.3833	114 BUARABA	1952	
040402	152.8522	-28.1181	120 FORTLAND	1959	1995
040400	152.4739	-27.9064	137 MOORANG	1919	
040397	152.1592	-27.6692	165 MT WHITESTONE	1950	
040395	152.1211	-27.7181	250 FORDSDALE	1953	
040394	152.7833	-28.2317	200 MOUNT BARNEY	1967	
040392	152.3830	-27.9000	213 TOWNSON EAST	1937	1978
040391	152.4700	-27.0867	66 WATTS BRIDGE	1951	1981
040388	152.2203	-27.6342	137 UPPER TENT HILL	1959	
040384	152.2239	-27.7219	175 MOUNT SYLVIA	1953	
040383	153.0500	-27.5000	25 GREENSLOPES REPATRIATION HOSPITAL	1965	
040382	152.0550	-27.2639	540 CROWS NEST	1893	

040381	152.8833	-28.2500	91	THE DIP	1966	1970
040380	152.3667	-28.1167	1097	CEDAR MOUNTAIN	1968	1970
040378	152.2992	-27.1931	120	TINTON	1952	1987
040374	152.4564	-27.7594	100	FRANKLYN VALE	1885	
040368	153.0483	-27.5200	31	LYNNDON PARK BOWLS CLUB	1965	
040343	152.8650	-27.0417	61	WAMURAN POST OFFICE	1915	
040342	153.2170	-28.1330	130	NUMINBAH VALLEY (CHIGIGUM FARM)	1964	1980
040329	152.4506	-27.4194	87	ATKINSONS DAM	1997	
040326	152.9750	-27.4433	40	ASHGROVE BOWLS CLUB	1964	
040325	152.9333	-27.4000	60	FERNY HILLS STATE SCHOOL	1964	1973
040324	152.9500	-27.4833	229	MOUNT COOT-THA	1964	1975
040320	153.1556	-27.4164	4	CALTEX REFINERIES (QLD) LTD	1964	
040319	153.3275	-27.7347	10	ROCKY POINT SUGAR MILL	1956	
040318	152.5642	-27.0258	104	KIRKLEAGH	1953	1991
040317	152.6667	-27.7508	46	RANGE VIEW	1961	
040314	152.8172	-27.7189	60	RIPLEY VALLEY	1961	
040312	152.9442	-27.7356	60	NEW BEITH	1961	
040311	152.1403	-27.0600	351	NUKINENDA	1901	1995
040310	152.3108	-27.7239	434	MT BERRYMAN	1961	
040309	152.6500	-27.1500	150	MT BYRON	1961	1980
040308	152.7710	-27.3350	625	MOUNT GLORIOUS	1933	
040306	153.1333	-27.6667	12	LOGANLEA ELLESLIE RD	1961	1986
040302	152.1158	-27.6242	165	FLAGSTONE CREEK	1961	
040300	152.3733	-27.4533	90	BALAAM HILL	1961	1999
040296	152.8167	-27.2500	60	KOBBLESTONE	1961	1975
040295	152.9142	-27.5292	50	KENMORE WAR VETS HOME	1962	
040291	153.3056	-27.6192	15	REDLAND BAY QLD UNI FARM	1961	
040290	152.7167	-28.1667	200	MAROON	1910	
040288	153.5036	-28.1661	5	COOLANGATTA AERO	1956	
040286	153.0667	-27.0000	2	PUMICESTONE POST OFFICE	1958	1973
040276	153.1833	-27.5167	20	CAPALABA POST OFFICE	1956	1978
040275	152.9333	-27.5167	20	KENMORE ST DAVID ST	1956	1978
040274	153.0750	-27.5400	64	MOUNT GRAVATT BOWLS CLUB	1955	
040270	152.1594	-27.3628	608	RAVENSBOURNE	1933	
040269	153.3640	-27.6363	12	KARRAGARRA ISLAND	1955	
040268	153.0267	-27.3931	30	CHERMSIDE BOWLS CLUB	1955	1995
040266	152.5500	-27.9830	100	ARATULA	1950	
040265	153.2500	-27.5210	11	ORMISTON (REDLANDS) H.R.S.	1953	
040263	153.0375	-27.3589	27	ZILLMERE POST OFFICE	1899	1993
040261	153.0167	-27.5500	12	YEERONGPILLY	1951	1969
040256	153.1667	-27.4500	12	WYNNUM RAILWAY STATION	1898	1985
040245	152.9925	-27.4933	9	TOOWONG BOWLS CLUB	1898	
040244	153.0500	-27.5830	70	SUNNYBANK BOWLING CLUB	1888	
040243	152.9833	-27.5167	25	GRACEVILLE BOWLS CLUB	1898	1987
040242	153.0700	-27.3233	1	SANDGATE POST OFFICE	1879	2000
040241	152.8861	-27.3617	53	SAMFORD CSIRO	1912	
040240	153.0358	-27.5519	9	SALISBURY BOWLS CLUB	1899	
040238	152.9833	-27.5500	19	OXLEY POST OFFICE	1898	1971
040237	153.0606	-27.3958	5	TOOMBUL BOWLS CLUB	1895	
040236	153.0667	-27.4167	17	NUDGEE	1911	1948
040235	153.1000	-27.4700	7	MURARRIE	1898	1997
040231	153.1830	-27.4500	30	MANLY	1898	
040230	152.8811	-27.4606	99	GOLD CREEK RESERVOIR	1885	
040229	152.9769	-27.4992	17	INDOOROOPILLY BOWLS CLUB	1887	
040227	152.9167	-27.6000	37	WOLSTON PARK HOSPITAL	1893	1973
040226	152.8975	-27.6081	20	GOODNA AMPOL	1870	1998
040225	152.9286	-27.4447	79	ENOGGERA RESERVOIR	1870	1996
040224	152.9967	-27.4217	33	ENOGGERA BOWLS CLUB	1899	
040223	153.1142	-27.4178	4	BRISBANE AERO	1929	2000
040222	153.0461	-27.4142	12	KALINGA BOWLS CLUB	1956	
040220	153.0500	-27.5000	6	COORPAROO BOWLS CLUB	1898	
040218	153.0833	-27.5000	12	CARINA HILL CRESCENT	1921	1975
040216	153.0500	-27.4500	20	BRISBANE SHOW GROUNDS	1889	
040215	153.0333	-27.4833	15	BRISBANE BOTANICAL GARDENS	1890	1984
040214	153.0310	-27.4780	38	BRISBANE REGIONAL OFFICE ROOF	1840	1994
040213	153.0097	-27.3236	15	BALD HILLS POST OFFICE	1895	1993
040212	153.0675	-27.4308	6	EAGLE FARM RACECOURSE	1920	

040211	153.0078	-27.5717	13	ARCHERFIELD AIRPORT	1929	
040209	153.5456	-27.4361	50	POINT LOOKOUT	1954	
040208	152.7258	-27.5508	80	VIEWMOUNT	1925	
040205	152.3744	-27.0897	99	TOOGOOLAWAH POST OFFICE	1909	
040204	153.0867	-27.3783	24	BANYO SEMINARY	1956	
040202	152.3806	-27.8206	200	THORNTON BVRT	1915	
040198	152.5117	-27.9764	134	TAROME	1911	
040197	153.1950	-27.9697	525	MT TAMBORINE FERN ST	1888	
040196	153.4167	-28.1331	12	TALLEBUDGERA GUINEAS CK RD	1899	
040192	153.2790	-28.2260	800	SPRINGBROOK FORESTRY	1914	
040190	153.4092	-27.9869	17	SOUTHPORT DRURY AVE	1881	
040189	152.5550	-27.1169	73	SOMERSET DAM	1936	
040188	152.6275	-27.2675	230	SIM JUES CREEK	1937	
040186	152.8331	-27.2994	65	SAMSONVALE	1919	
040185	153.4000	-27.6450	10	RUSSELL ISLAND	1914	
040184	152.5922	-27.6361	43	ROSEWOOD CABANDA LODGE	1894	
040183	152.4797	-27.8519	100	ROSEVALE	1909	
040182	153.1361	-28.2322	923	GREEN MOUNTAINS	1916	
040181	152.6830	-27.9170	140	ROADVALE	1907	1983
040180	153.1008	-27.2517	10	MARGATE COLLINS ST	1886	1989
040179	152.8667	-27.6000	20	REDBANK POST OFFICE	1888	1978
040178	152.8639	-28.2150	96	RATHDOWNEY POST OFFICE	1912	
040175	153.5219	-27.4275	10	POINT LOOKOUT BOWLS CLUB	1947	
040171	152.9847	-27.2708	8	PETRIE AUST PAPER MILLS	1886	
040170	152.0533	-27.3228	655	PECHEY FORESTRY	1927	
040167	152.7694	-28.3258	250	PALEN CREEK CORRECTIONAL	1936	
040166	153.3119	-27.8914	7	OXENFORD COTTONWOOD PLACE	1894	
040163	152.9167	-28.2000	61	INNIS PLAIN	1925	1972
040162	153.2114	-28.1633	152	NUMINBAH STATE FARM	1941	
040160	153.3175	-28.0092	25	NERANG GILSTON RD	1887	
040159	152.9667	-27.2000	45	NARANGBA RAILWAY STN	1920	1987
040156	152.9411	-28.1808	76	INNISPLAIN	1913	
040154	152.5000	-27.2000	60	MURRUMBA (FAIRVIEW)	1926	1974
040153	152.0500	-27.4670	260	MURPHYS CREEK	1895	1985
040150	153.0933	-27.9050	61	MUNDOOLIN	1881	
040149	152.5967	-28.1400	150	MOUNTAIN VIEW	1924	1992
040147	152.7880	-27.4010	450	MOUNT NEBO	1947	
040145	152.7800	-27.0697	495	MT MEE	1909	
040142	152.7997	-27.5386	20	MT CROSBY	1894	
040141	153.2042	-27.6158	220	MOUNT COTTON WEST	1915	
040140	152.5310	-27.0912	600	MOUNT BRISBANE	1890	
040139	152.6000	-28.0670	110	MOUNT ALFORD	1911	
040135	152.5517	-28.0317	183	MOOGERAH DAM	1917	
040124	152.6053	-27.5675	90	MARBURG - WARREGO HIGHWAY	1887	
040120	152.5750	-27.4622	50	LOWOOD DON ST	1887	
040115	152.7500	-27.4830	60	LAKE MANCHESTER	1917	
040114	152.3919	-27.6322	34	LAIDLEY POST OFFICE	1889	1995
040108	152.7478	-27.5519	30	KHOLO	1940	
040107	153.0367	-28.0500	31	BRUFF HILL	1917	1998
040104	152.6236	-27.9486	80	ENGLESBERG VILLAGE	1887	
040101	152.7580	-27.6190	20	IPSWICH COMPOSITE	1870	
040097	153.0133	-28.2150	110	CHRISTMAS CREEK	1912	1993
040096	152.1236	-27.5503	141	HELIDON POST OFFICE	1870	
040095	152.4628	-27.5675	113	HATTONVALE STORE	1908	
040094	152.6675	-27.8117	55	HARRISVILLE POST OFFICE	1896	
040091	152.4675	-27.6597	76	GRANDCHESTER SYMES ST	1894	
040083	152.2981	-27.5425	70	GATTON ALLAN STREET	1894	
040082	152.3358	-27.5508	94	UNIVERSITY OF QUEENSLAND GATTON	1897	
040080	153.0170	-28.2650	175	FOXLEY	1923	
040079	152.3567	-27.5900	92	FOREST HILL POST OFFICE	1894	
040076	152.1683	-27.1533	501	ESK DALE WEST	1933	1990
040075	152.4220	-27.2400	100	ESK	1886	
040066	152.8333	-27.6000	76	DINMORE POST OFFICE	1894	1979
040064	152.2310	-27.3062	470	DEONGWAR STATE FOREST	1937	1969
040063	152.8247	-27.1967	52	DAYBORO POST OFFICE	1931	
040056	152.5014	-27.3914	81	COOMINYA POST OFFICE	1916	
040052	153.5330	-28.1830	6	COOLANGATTA COMPOSITE	1927	1981

040047	153.2750	-27.5261	8	CLEVELAND BOWLS CLUB	1870	
040044	153.0833	-28.2500	60	DARLINGTON	1917	1974
040043	153.4650	-27.0330	99	CAPE MORETON LIGHTHOUSE	1869	
040042	153.1664	-28.0142	100	CANUNGRA FINCH ROAD	1915	
040041	152.8617	-27.3967	60	CAMP MOUNTAIN (DAVIDSON ROAD)	1926	
040038	152.9517	-27.0850	4	CABOOLTURE POST OFFICE	1870	1999
040035	152.9560	-27.1612	16	BURPENGARY	1898	
040034	153.4500	-28.0830	10	BURLEIGH HEADS	1939	1968
040030	152.4830	-28.2330	840	BRYN EURYN	1917	1973
040027	153.1658	-27.0892	3	BONGAREE BOWLS CLUB	1931	1991
040024	152.6919	-27.9925	70	BOONAH STARK AVE	1898	
040015	153.1903	-28.1467	520	BEECHMONT BINNA BURRA ROAD	1919	
040014	152.9900	-28.0000	46	BEAUDESERT COMPOSITE	1887	
040012	152.8000	-28.2500	90	BARNEY VIEW	1947	1984
040011	152.3650	-27.7300	142	LAIDLEY CREEK	1964	1990
040004	152.7114	-27.6294	27	AMBERLEY AMO	1941	
040000	153.1000	-27.9500	60	ABBOTSFORD	1909	1974

Appendix B
Murwillumbah Rainfall 1981-2000

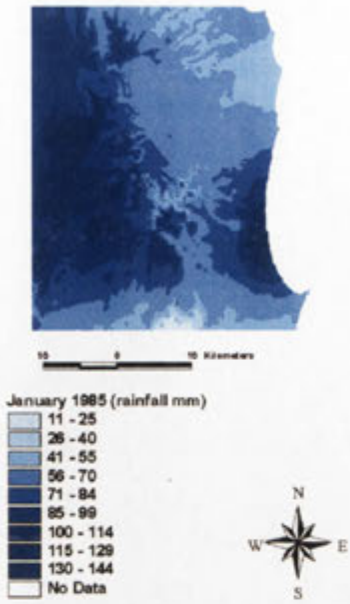
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	162.00	87.00	115.00	112.00	72.00	69.00	10.00	13.00	7.00	107.00	199.00	103.00
1999	207.00	259.00	337.00	292.00	155.00	422.00	144.00	123.00	123.00	141.00	99.00	143.00
1998	81.00	93.00	88.00	123.00	98.00	20.00	49.00	140.00	154.00	25.00	132.00	154.00
1997	254.00	136.00	47.00	14.00	282.00	53.00	33.00	6.00	72.00	81.00	186.00	173.00
1996	310.00	206.00	108.00	20.00	491.00	57.00	47.00	44.00	9.00	44.00	168.00	210.00
1995	88.00	514.00	88.00	58.00	66.00	49.00	3.00	47.00	22.00	60.00	193.00	211.00
1994	241.00	204.00	360.00	84.00	66.00	37.00	40.00	35.00	23.00	27.00	26.00	195.00
1993	88.00	146.00	133.00	49.00	64.00	9.00	112.00	29.00	88.00	69.00	123.00	152.00
1992	133.00	205.00	296.00	207.00	152.00	20.00	70.00	6.00	18.00	38.00	116.00	142.00
1991	106.00	201.00	143.00	41.00	97.00	65.00	81.00	0.00	1.00	64.00	22.00	317.00
1990	181.00	408.00	247.00	452.00	215.00	113.00	25.00	3.00	17.00	27.00	78.00	114.00
1989	485.00	164.00	239.00	752.00	185.00	40.00	50.00	55.00	18.00	30.00	177.00	200.00
1988	274.00	41.00	215.00	727.00	9.00	156.00	200.00	77.00	118.00	17.00	50.00	319.00
1987	64.00	112.00	457.00	74.00	505.00	104.00	73.00	255.00	3.00	133.00	21.00	165.00
1986	131.00	55.00	54.00	41.00	95.00	10.00	31.00	35.00	13.00	112.00	154.00	115.00
1985	57.00	326.00	353.00	110.00	184.00	40.00	157.00	14.00	41.00	156.00	50.00	67.00
1984	228.00	156.00	90.00	343.00	56.00	192.00	116.00	32.00	18.00	205.00	221.00	122.00
1983	70.00	168.00	213.00	119.00	271.00	380.00	64.00	98.00	112.00	92.00	353.00	289.00
1982	261.00	93.00	170.00	98.00	89.00	21.00	29.00	72.00	97.00	172.00	40.00	105.00
1981	133.00	324.00	39.00	210.00	208.00	10.00	30.00	33.00	11.00	82.00	192.00	188.00
1980	263.00	145.00	30.00	40.00	543.00	44.00	36.00	17.00	0.00	42.00	90.00	260.00
1979	271.00	160.00	111.00	118.00	11.00	174.00	107.00	2.00	2.00	75.00	127.00	77.00
1978	146.00	100.00	765.00	63.00	74.00	16.00	24.00	71.00	74.00	77.00	91.00	196.00
1977	52.00	221.00	322.00	109.00	119.00	10.00	67.00	10.00	25.00	93.00	113.00	41.00
1976	214.00	625.00	404.00	96.00	124.00	63.00	62.00	3.00	49.00	77.00	156.00	112.00
1975	95.00	234.00	240.00	83.00	28.00	63.00	21.00	63.00	90.00	163.00	141.00	316.00
1974	820.00	151.00	611.00	422.00	100.00	231.00	4.00	117.00	46.00	60.00	219.00	91.00
1973	250.00	683.00	66.00	73.00	111.00	62.00	429.00	51.00	21.00	137.00	99.00	117.00
1972	581.00	551.00	220.00	361.00	174.00	80.00	12.00	28.00	31.00	610.00	134.00	41.00
1971	393.00	353.00	193.00	52.00	20.00	9.00	43.00	37.00	69.00	26.00	45.00	146.00
1970	148.00	188.00	224.00	87.00	15.00	22.00	26.00	72.00	59.00	148.00	131.00	529.00
1969	16.00	85.00	122.00	56.00	297.00	16.00	53.00	156.00	12.00	253.00	209.00	53.00
1968	313.00	247.00	126.00	62.00	96.00	5.00	42.00	107.00	4.00	10.00	33.00	91.00
1967	303.00	102.00	425.00	109.00	130.00	757.00	58.00	70.00	3.00	161.00	42.00	76.00
1966	19.00	170.00	38.00	89.00	44.00	198.00	5.00	147.00	53.00	90.00	131.00	89.00
1965	176.00	68.00	14.00	68.00	75.00	206.00	350.00	111.00	41.00	42.00	45.00	261.00
1964	164.00	255.00	368.00	159.00	140.00	23.00	46.00	21.00	63.00	49.00	99.00	89.00
1963	242.00	185.00	562.00	233.00	434.00	53.00	1.00	67.00	74.00	53.00	192.00	235.00
1962	385.00	146.00	293.00	134.00	113.00	19.00	336.00	246.00	52.00	29.00	61.00	437.00
1961	159.00	320.00	121.00	143.00	122.00	62.00	103.00	58.00	58.00	198.00	294.00	243.00
1960	110.00	207.00	178.00	88.00	93.00	26.00	49.00	15.00	6.00	81.00	127.00	78.00
1959	262.00	355.00	493.00	106.00	50.00	63.00	130.00	31.00	160.00	141.00	245.00	206.00
1958	85.00	148.00	241.00	275.00	13.00	412.00	7.00	301.00	71.00	39.00	93.00	241.00
1957	261.00	185.00	75.00	62.00	4.00	34.00	119.00	136.00	10.00	57.00	62.00	37.00
1956	192.00	973.00	268.00	137.00	257.00	139.00	30.00	12.00	12.00	50.00	24.00	221.00
1955	115.00	95.00	419.00	220.00	467.00	57.00	40.00	6.00	41.00	106.00	72.00	474.00
1954	132.00	851.00	77.00	69.00	209.00	62.00	289.00	80.00	86.00	255.00	139.00	54.00
1953	295.00	671.00	326.00	38.00	39.00	0.00	28.00	65.00	13.00	90.00	96.00	116.00
1952	17.00	157.00	326.00	123.00	105.00	220.00	38.00	144.00	30.00	91.00	24.00	66.00
1951	496.00	109.00	284.00	64.00	86.00	186.00	0.00	23.00	22.00	41.00	6.00	106.00
1950	195.00	523.00	296.00	116.00	17.00	275.00	450.00	57.00	58.00	122.00	159.00	90.00
1949	189.00	208.00	403.00	49.00	62.00	130.00	70.00	9.00	43.00	191.00	170.00	37.00
1948	196.00	134.00	347.00	123.00	176.00	377.00	13.00	41.00	148.00	0.00	94.00	67.00
1947	576.00	323.00	344.00	173.00	99.00	7.00	4.00	25.00	63.00	49.00	135.00	225.00
1946	161.00	402.00	345.00	163.00	10.00	1.00	2.00	10.00	80.00	98.00	40.00	51.00
1945	80.00	209.00	108.00	195.00	132.00	567.00	192.00	16.00	44.00	83.00	54.00	80.00
1944	418.00	59.00	121.00	27.00	45.00	31.00	170.00	144.00	52.00	25.00	127.00	43.00
1943	127.00	126.00	82.00	80.00	45.00	19.00	3.00	22.00	87.00	203.00	274.00	281.00
1942	54.00	623.00	56.00	101.00	59.00	52.00	78.00	17.00	13.00	190.00	135.00	294.00
1941	366.00	145.00	286.00	132.00	102.00	76.00	7.00	9.00	17.00	4.00	69.00	27.00
1940	103.00	131.00	300.00	46.00	39.00	79.00	7.00	66.00	10.00	52.00	48.00	269.00
1939	157.00	60.00	626.00	163.00	65.00	55.00	32.00	60.00	7.00	126.00	80.00	39.00
1938	406.00	334.00	373.00	112.00	445.00	106.00	64.00	48.00	22.00	71.00	31.00	10.00
1937	84.00	232.00	469.00	35.00	9.00	91.00	79.00	122.00	7.00	211.00	433.00	144.00
1936	121.00	108.00	206.00	18.00	196.00	54.00	28.00	8.00	46.00	47.00	42.00	157.00
1935	121.00	211.00	116.00	128.00	102.00	4.00	111.00	61.00	139.00	93.00	38.00	142.00
1934	170.00	340.00	99.00	451.00	290.00	14.00	213.00	61.00	48.00	72.00	162.00	187.00
1933	345.00	107.00	61.00	372.00	71.00	87.00	138.00	3.00	80.00	107.00	307.00	163.00
1932	40.00	63.00	48.00	280.00	117.00	47.00	13.00	9.00	122.00	86.00	64.00	20.00
1931	128.00	745.00	415.00	310.00	81.00	4.00	37.00	86.00	50.00	46.00	207.00	227.00
1930	227.00	90.00	226.00	148.00	392.00	438.00	8.00	143.00	22.00	75.00	58.00	77.00
1929	243.00	299.00	367.00	376.00	65.00	68.00	199.00	26.00	9.00	174.00	46.00	53.00
1928	255.00	609.00	62.00	483.00	134.00	63.00	87.00	46.00	0.00	39.00	36.00	63.00
1927	692.00	109.00	285.00	86.00	1.00	56.00	6.00	2.00	159.00	107.00	397.00	170.00

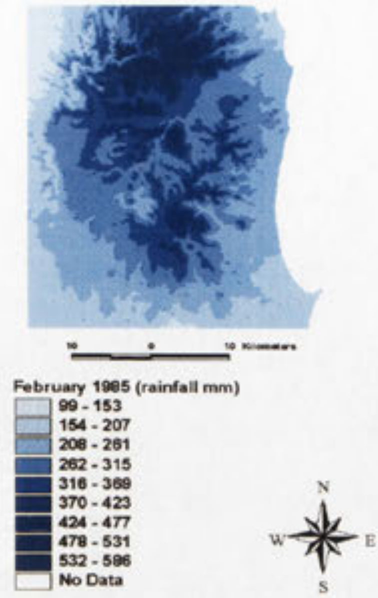
1926	111.00	21.00	136.00	408.00	89.00	224.00	43.00	32.00	57.00	58.00	11.00	298.00
1925	326.00	106.00	648.00	105.00	299.00	285.00	27.00	93.00	7.00	26.00	199.00	240.00
1924	114.00	199.00	92.00	52.00	66.00	226.00	281.00	36.00	63.00	69.00	116.00	64.00
1923	38.00	34.00	83.00	472.00	0.00	72.00	56.00	88.00	28.00	10.00	10.00	157.00
1922	66.00	516.00	116.00	13.00	139.00	46.00	151.00	13.00	100.00	40.00	22.00	152.00
1921	360.00	55.00	387.00	276.00	265.00	247.00	443.00	61.00	148.00	41.00	53.00	382.00
1920	570.00	91.00	100.00	172.00	141.00	95.00	242.00	41.00	134.00	121.00	91.00	154.00
1919	55.00	46.00	385.00	132.00	533.00	44.00	14.00	11.00	4.00	50.00	61.00	102.00
1918	274.00	43.00	127.00	136.00	144.00	14.00	8.00	59.00	40.00	19.00	109.00	111.00
1917	206.00	173.00	240.00	28.00	62.00	14.00	7.00	27.00	165.00	45.00	555.00	148.00
1916	98.00	271.00	39.00	285.00	67.00	52.00	36.00	65.00	136.00	181.00	138.00	230.00
1915	177.00	178.00	6.00	17.00	158.00	14.00	49.00	78.00	40.00	1.00	50.00	95.00
1914	88.00	174.00	281.00	41.00	132.00	162.00	125.00	57.00	83.00	234.00	57.00	113.00
1913	142.00	405.00	192.00	316.00	208.00	177.00	95.00	0.00	96.00	39.00	32.00	69.00
1912	31.00	123.00	320.00	55.00	25.00	285.00	105.00	47.00	32.00	105.00	114.00	49.00
1911	589.00	268.00	137.00	138.00	21.00	2.00	138.00	111.00	21.00	71.00	31.00	72.00
1910	390.00	132.00	334.00	152.00	41.00	248.00	4.00	10.00	111.00	79.00	154.00	236.00
1909	52.00	111.00	110.00	177.00	45.00	48.00	93.00	44.00	71.00	98.00	126.00	201.00
1908	127.00	275.00	300.00	106.00	87.00	5.00	32.00	308.00	39.00	408.00	126.00	58.00
1907	196.00	271.00	384.00	56.00	239.00	351.00	33.00	37.00	0.00	21.00	137.00	138.00
1906	194.00	376.00	336.00	30.00	353.00	85.00	1.00	128.00	148.00	242.00	85.00	231.00
1905	130.00	141.00	207.00	287.00	210.00	16.00	5.00	37.00	33.00	93.00	74.00	110.00
1904	113.00	24.00	275.00	380.00	287.00	11.00	59.00	23.00	32.00	77.00	40.00	143.00
1903	170.00	116.00	165.00	116.00	198.00	178.00	205.00	58.00	143.00	121.00	125.00	55.00
1902	118.00	105.00	37.00	42.00	16.00	9.00	38.00	17.00	35.00	132.00	94.00	99.00
1901	65.00	159.00	427.00	128.00	199.00	116.00	31.00	104.00	82.00	93.00	49.00	15.00
1900	114.00	72.00	62.00	30.00	328.00	113.00	261.00	24.00	90.00	3.00	116.00	95.00
1899	229.00	176.00	74.00	134.00	71.00	91.00	266.00	168.00	135.00	70.00	67.00	232.00
1898	380.00	403.00	485.00	74.00	101.00	191.00	42.00	91.00	85.00	82.00	62.00	86.00
1897	53.00	71.00	239.00	2.00	91.00	157.00	204.00	45.00	113.00	52.00	76.00	360.00
1896	110.00	569.00	127.00	48.00	52.00	28.00	65.00	12.00	28.00	12.00	436.00	171.00
1895	938.00	199.00	49.00	105.00	41.00	0.00	5.00	24.00	70.00	62.00	49.00	192.00
1894	463.00	225.00	689.00	131.00	69.00	77.00	2.00	28.00	83.00	148.00	82.00	240.00
1893	367.00	1087.00	320.00	148.00	30.00	339.00	64.00	153.00	36.00	71.00	124.00	14.00
1892	132.00	41.00	697.00	539.00	234.00	235.00	62.00	33.00	133.00	232.00	95.00	149.00
1891	350.00	104.00	239.00	75.00	405.00	190.00	74.00	188.00	114.00	93.00	92.00	129.00
1890	589.00	519.00	906.00	364.00	127.00	99.00	26.00	9.00	93.00	35.00	78.00	139.00
1889	70.00	33.00	252.00	261.00	15.00	5.00	425.00	314.00	81.00	107.00	153.00	227.00
1888	89.00	520.00	58.00	63.00	26.00	63.00	10.00	15.00	86.00	82.00	23.00	172.00
1887	414.00	309.00	839.00	102.00	223.00	21.00	298.00	391.00	39.00	16.00	99.00	120.00
1886	242.00	66.00	56.00	51.00	102.00	265.00	178.00	62.00	176.00	150.00	312.00	226.00
1885	91.00	77.00	48.00	78.00	51.00	89.00	7.00	8.00	30.00	44.00	73.00	158.00
1884	23.00	111.00	150.00	241.00	362.00	56.00	145.00	30.00	56.00	36.00	77.00	51.00
1883	599.00	176.00	150.00	125.00	124.00	6.00	11.00	17.00	63.00	47.00	31.00	50.00
1882	30.00	330.00	149.00	165.00	47.00	122.00	108.00	35.00	11.00	293.00	96.00	223.00
1881	115.00	168.00	187.00	133.00	119.00	73.00	20.00	66.00	62.00	71.00	277.00	41.00

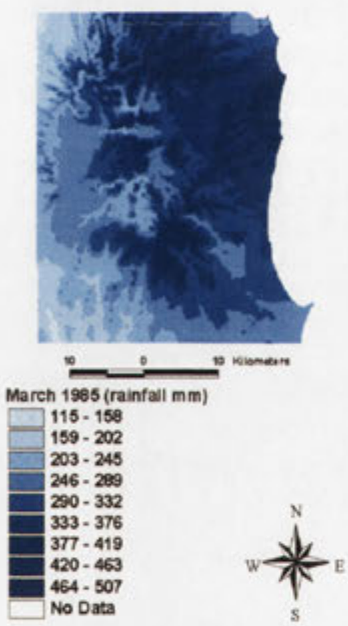
Tweed Heads Rainfall 1921-2000

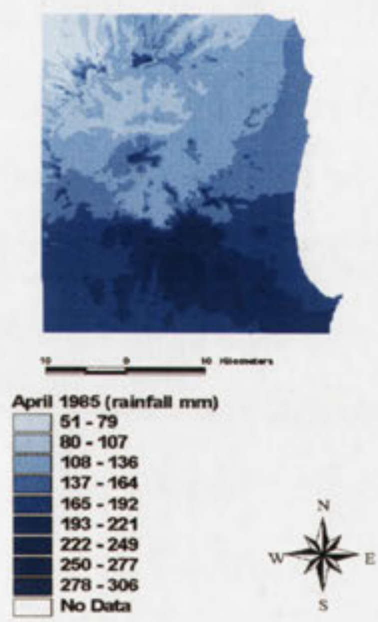
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	193.00	219.00	126.00	124.00	66.00	196.00	26.00	18.00	11.00	126.00	203.00	125.00
1999	341.00	255.00	346.00	269.00	150.00	494.00	254.00	122.00	51.00	265.00	178.00	136.00
1998	50.00	107.00	39.00	313.00	237.00	26.00	75.00	65.00	215.00	33.00	125.00	154.00
1997	177.00	82.00	66.00	36.00	340.00	63.00	104.00	8.80	72.00	106.00	204.00	129.00
1996	255.00	185.00	149.00	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	130.00
1995	95.00	394.00	111.00	125.00	101.00	53.00	2.60	95.00	18.00	21.00	226.00	190.00
1994	197.60	174.60	550.60	105.40	231.80	69.40	60.20	35.60	30.00	73.80	23.80	124.80
1993	96.40	170.20	157.60	138.80	117.40	41.20	187.80	70.00	104.20	101.80	63.80	180.60
1992	78.60	218.40	287.00	139.80	163.40	55.40	85.40	13.00	24.80	49.80	121.60	102.00
1991	107.20	127.50	64.70	37.80	262.30	158.20	158.60	2.50	0.40	126.20	47.40	261.00
1990	228.80	402.30	337.30	348.30	333.60	106.70	27.60	5.20	48.80	106.60	107.00	68.30
1989	168.10	197.30	192.80	391.30	210.70	68.70	58.00	80.60	23.80	51.80	218.50	265.60
1988	434.60	51.00	345.70	728.50	7.00	89.00	228.80	125.40	167.60	31.20	80.90	302.80
1987	82.30	111.40	637.40	128.70	376.00	141.60	72.00	153.20	0.00	139.80	24.20	171.80
1986	97.90	14.70	93.70	75.90	117.00	26.60	67.90	61.40	15.00	81.20	172.50	138.00
1985	57.20	185.00	314.70	146.40	156.80	51.00	216.40	26.80	78.20	72.20	96.90	74.20
1984	180.00	176.10	68.80	408.90	118.40	286.20	92.70	23.00	68.40	346.40	264.00	102.00
1983	244.80	82.30	151.20	137.60	383.00	294.40	91.00	114.40	94.80	63.40	397.60	440.50
1982	189.00	135.40	108.60	115.00	108.20	15.90	48.40	50.50	231.10	136.60	2.00	68.60
1981	68.90	322.00	46.80	231.40	164.80	5.80	36.80	43.00	4.60	34.00	170.70	149.20
1980	109.60	223.80	39.00	48.20	509.30	47.00	61.60	25.60	0.00	76.00	57.40	141.60
1979	272.40	160.20	97.60	199.00	9.60	121.00	128.40	8.00	7.40	83.00	38.00	70.90
1978	311.60	112.00	678.20	82.20	102.80	27.70	35.60	71.00	79.20	73.90	122.60	245.60
1977	109.80	227.80	371.20	164.00	139.80	19.10	52.10	10.20	40.80	70.00	66.80	22.00
1976	153.60	357.40	-99.00	116.00	228.80	112.50	105.30	4.40	69.40	87.00	176.00	105.20
1975	85.00	257.50	-99.00	112.40	45.40	115.80	23.00	37.30	93.40	127.40	150.60	113.80
1974	514.90	80.90	740.80	493.00	127.00	359.90	0.00	67.80	62.20	115.40	184.00	64.00
1973	88.80	514.50	119.70	168.20	90.20	67.00	393.10	37.30	25.00	186.90	127.10	116.80
1972	374.70	427.00	302.50	242.10	189.60	121.70	17.00	36.60	35.40	640.40	195.00	49.60
1971	376.60	272.40	120.00	63.30	23.10	29.50	56.40	57.10	67.00	35.60	75.70	116.60
1970	154.70	316.90	208.90	58.50	1.80	19.10	10.60	69.30	63.70	134.60	153.00	462.40
1969	33.10	130.00	78.40	71.90	239.20	15.00	61.80	107.40	37.60	507.70	248.80	100.60
1968	199.40	160.90	126.20	110.30	114.60	27.80	81.80	61.00	14.50	0.30	36.60	95.00
1967	345.90	126.60	399.50	121.60	219.40	634.50	64.50	86.20	3.00	110.80	164.10	87.90
1966	16.40	122.20	63.00	160.20	88.80	306.90	37.90	167.30	74.90	104.90	104.80	130.20
1965	107.40	98.40	22.80	107.00	95.70	143.90	263.90	84.20	29.80	68.00	11.40	230.70
1964	53.90	421.20	310.00	135.50	120.40	31.20	28.20	41.50	60.50	50.80	34.60	64.20
1963	210.80	127.70	527.40	212.30	314.20	96.40	3.30	71.70	27.40	41.40	144.80	204.20
1962	295.00	221.60	296.70	137.50	137.20	28.50	283.50	115.10	57.10	38.60	73.10	178.60
1961	171.70	220.90	103.70	71.70	175.50	41.30	55.10	51.10	81.80	124.90	347.00	285.80
1960	131.50	170.60	224.90	67.60	87.90	24.60	38.20	9.40	0.30	98.40	106.40	55.20
1959	314.60	148.60	302.50	93.10	52.90	92.00	128.30	22.50	140.40	152.00	194.20	131.60
1958	83.40	109.20	125.90	293.30	55.10	296.00	7.60	214.10	67.10	32.90	69.50	131.30
1957	225.90	133.60	110.60	87.20	2.30	44.00	146.90	144.60	12.50	64.00	73.90	44.20
1956	194.40	897.90	136.80	99.60	165.90	134.80	19.30	7.10	16.50	24.00	43.70	238.00
1955	109.70	65.90	327.60	215.60	235.50	61.00	116.70	4.60	60.90	91.60	7.60	487.20
1954	89.10	883.40	109.30	40.80	320.90	67.80	248.70	167.90	144.40	309.60	127.50	100.10
1953	235.90	850.30	334.40	18.60	71.30	0.00	55.90	97.30	37.50	74.80	79.70	200.50
1952	27.00	181.70	442.20	175.40	76.00	221.00	48.10	156.10	65.90	144.80	17.50	47.50
1951	609.90	128.80	232.70	39.20	130.10	277.70	1.80	12.70	36.10	46.00	13.70	71.50
1950	132.30	440.80	195.90	171.90	21.10	264.90	395.30	120.90	26.20	72.50	163.60	101.70
1949	104.50	189.50	271.40	88.30	94.30	167.40	66.60	10.20	20.90	211.50	32.70	37.50
1948	265.10	58.40	305.20	205.40	126.70	442.20	40.70	73.10	216.10	0.00	127.00	39.50
1947	460.20	354.40	297.30	234.70	156.20	6.90	5.80	89.60	96.90	50.00	100.40	119.80
1946	187.70	256.00	266.80	199.80	23.60	10.20	1.30	18.10	97.30	121.80	32.00	38.90
1945	47.80	204.20	271.10	233.90	157.60	363.80	79.70	26.20	88.30	193.30	86.00	115.00
1944	408.70	22.20	113.80	44.00	46.40	66.30	303.00	112.80	46.30	39.30	73.40	27.20
1943	147.40	176.50	123.70	110.50	153.20	52.90	5.10	21.70	90.10	234.80	230.50	300.70
1942	45.70	487.80	75.40	128.90	88.70	103.90	61.90	36.40	13.50	182.90	211.40	280.40
1941	295.10	190.00	394.10	142.30	146.50	94.80	21.80	1.80	31.20	16.60	64.70	19.50
1940	93.80	112.30	275.30	50.40	42.20	116.80	18.80	79.60	15.20	42.30	55.20	191.20
1939	75.20	57.40	597.50	153.90	144.40	49.30	61.40	59.90	2.30	199.60	194.20	85.90
1938	208.00	176.40	238.40	140.70	353.70	212.10	106.80	60.40	8.40	114.50	36.80	8.30
1937	83.20	241.50	644.50	66.80	26.70	107.40	123.60	118.80	4.80	135.80	390.80	106.90
1936	120.60	64.30	177.20	47.20	264.70	71.20	57.10	16.60	46.40	59.50	37.30	114.10
1935	148.40	148.70	184.90	101.60	111.10	6.10	79.60	44.30	112.80	185.90	26.40	71.30
1934	150.80	416.60	59.40	315.60	456.50	31.80	184.90	48.90	70.60	144.30	136.80	226.50
1933	220.00	76.80	122.90	370.10	66.80	129.10	137.90	10.70	113.70	53.40	147.20	215.10
1932	21.20	138.80	55.00	181.20	214.20	77.50	32.40	16.90	153.90	99.90	141.90	12.50
1931	123.50	709.70	347.70	281.70	126.00	35.60	58.60	75.60	26.50	114.80	196.00	253.30
1930	209.30	99.30	241.40	196.40	355.70	335.60	36.30	160.20	37.60	75.70	46.60	92.80
1929	110.40	291.10	325.70	320.30	164.10	143.60	18.10	31.80	14.20	86.20	40.10	90.10
1928	321.50	579.20	89.00	429.10	97.10	60.90	38.10	67.80	0.00	40.20	29.90	84.20
1927	540.80	117.40	340.40	162.10	5.80	93.70	10.10	5.90	100.30	180.60	290.10	298.70
1926	122.60	16.00	181.60	240.60	94.50	230.90	39.20	26.40	124.70	35.50	23.10	252.00
1925	253.20	98.90	463.60	91.00	346.70	152.10	20.80	89.90	19.50	40.40	291.40	177.30
1924	75.30	271.00	64.00	107.40	126.90	311.10	183.90	49.70	80.80	73.50	265.60	100.70
1923	83.90	185.30	108.50	457.90	4.10	61.40	88.00	129.10	29.90	10.20	37.90	185.40
1922	58.10	360.00	132.10	11.10	122.50	70.90	210.00	20.80	116.30	38.30	36.30	85.90
1921	315.50	98.10	341.30	391.40	194.90	246.70	294.10	19.50	130.60	39.60	80.00	270.80

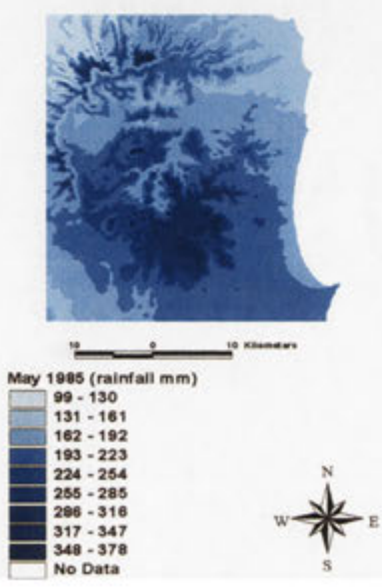
Appendix C. Rainfall Surfaces for 1985 (Rainfall in mm)

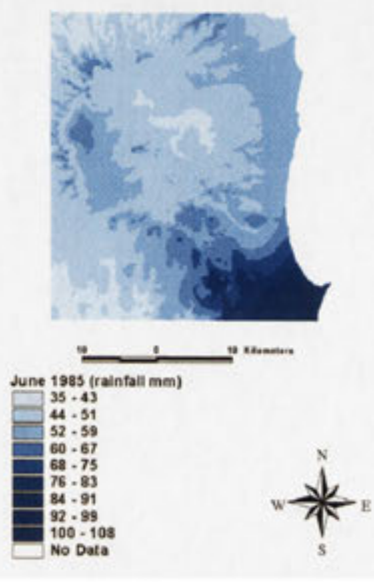


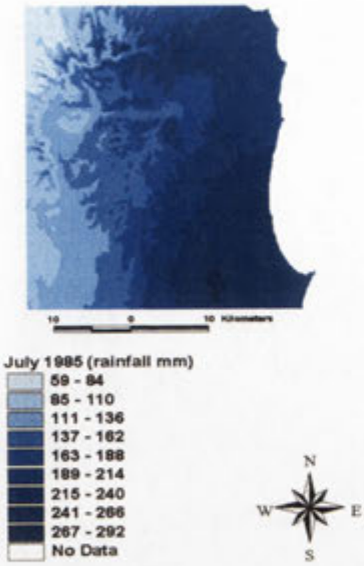


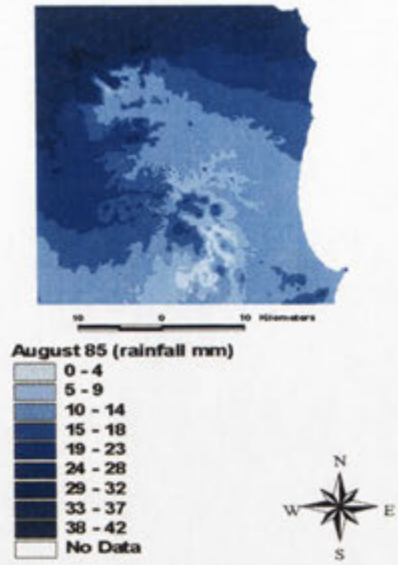


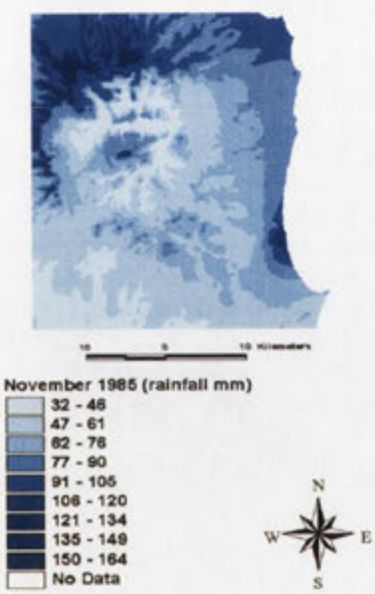


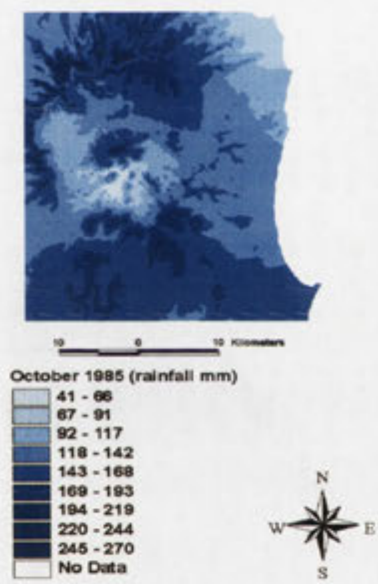


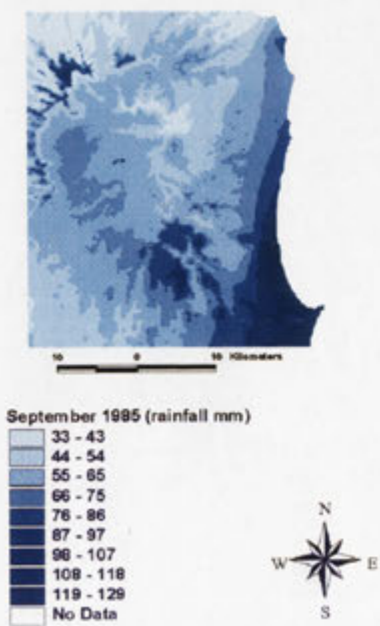


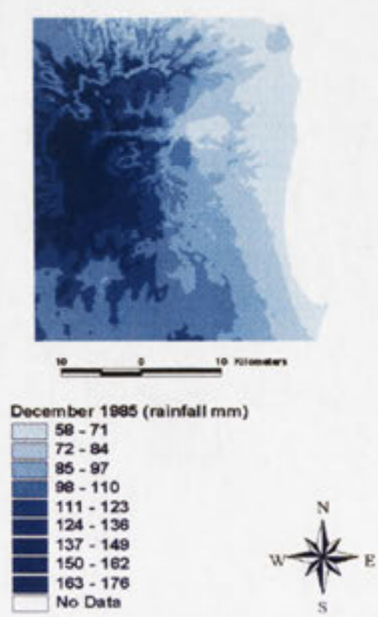

10 0 10 Kilometers
July 1985 (rainfall mm)
59 - 84
85 - 110
111 - 136
137 - 162
163 - 188
189 - 214
215 - 240
241 - 266
267 - 292
No Data
N
W
E
S


10 0 10 Kilometers
August 85 (rainfall mm)
0 - 4
5 - 9
10 - 14
15 - 18
19 - 23
24 - 28
29 - 32
33 - 37
38 - 42
No Data
N
W
E
S

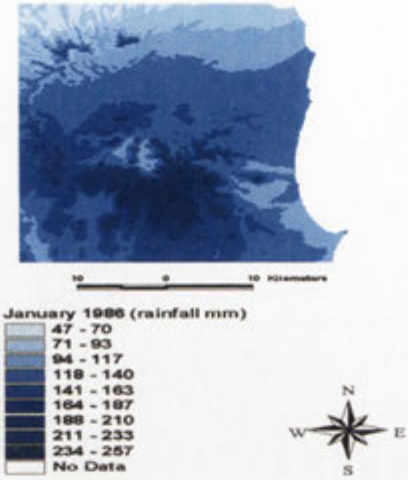

10 0 10 Kilometers
November 1985 (rainfall mm)
32 - 46
47 - 61
62 - 76
77 - 90
91 - 105
106 - 120
121 - 134
135 - 149
150 - 164
No Data
N
W
E
S

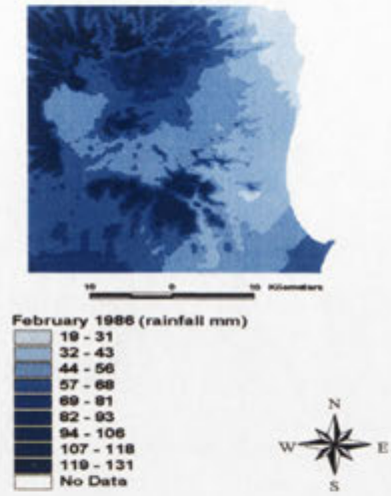

10 0 10 Kilometers
October 1985 (rainfall mm)
41 - 66
67 - 91
92 - 117
118 - 142
143 - 168
169 - 193
194 - 219
220 - 244
245 - 270
No Data
N
W
E
S

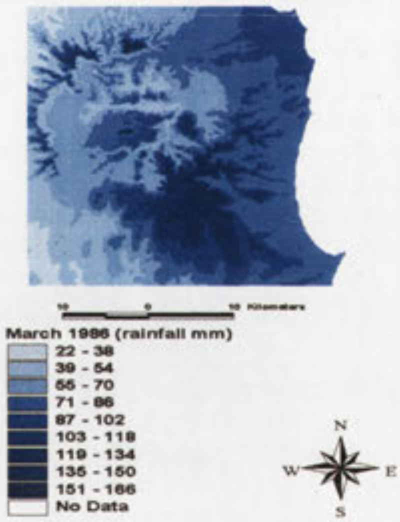

10 0 10 Kilometers
September 1985 (rainfall mm)
33 - 43
44 - 54
55 - 65
66 - 75
76 - 86
87 - 97
98 - 107
108 - 118
119 - 129
No Data
N
W
E
S

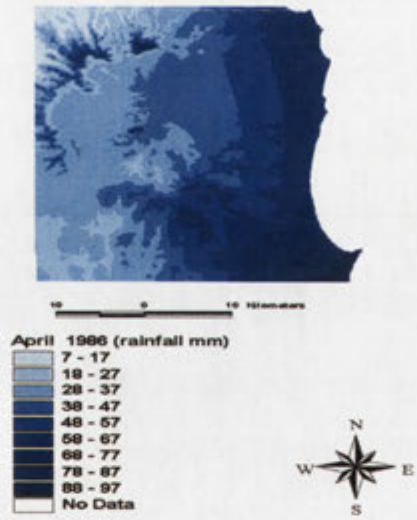

10 0 10 Kilometers
December 1985 (rainfall mm)
58 - 71
72 - 84
85 - 97
98 - 110
111 - 123
124 - 136
137 - 149
150 - 162
163 - 176
No Data
N
W
E
S

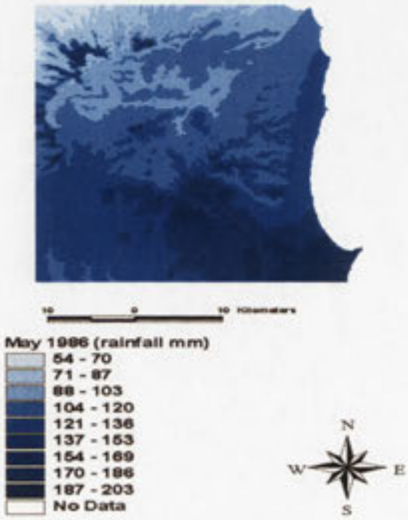
Appendix C. Rainfall Surfaces for 1986-87 (Rainfall in mm)

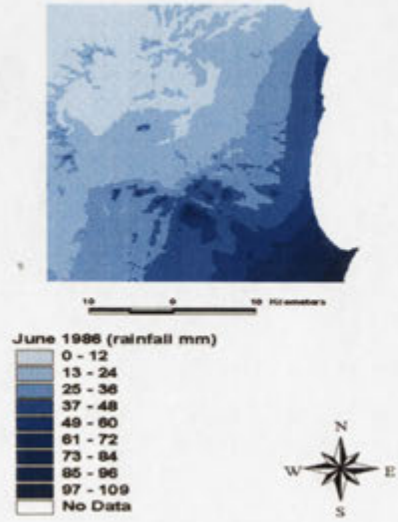


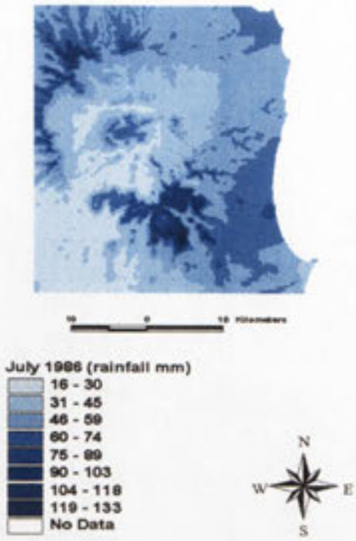


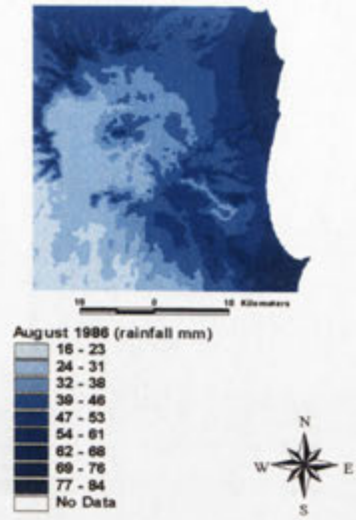


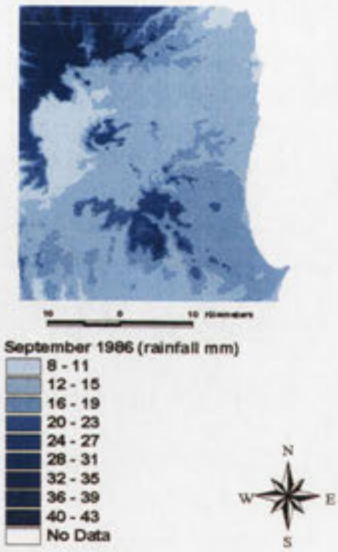


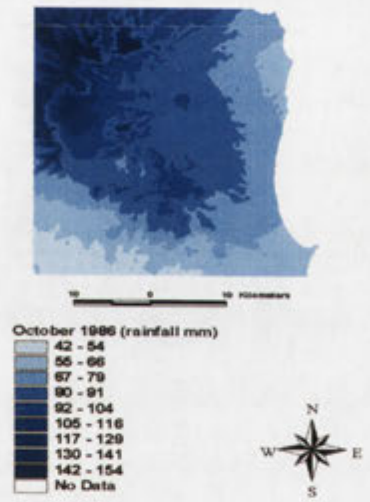


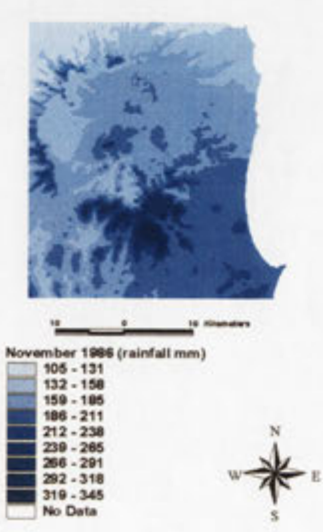


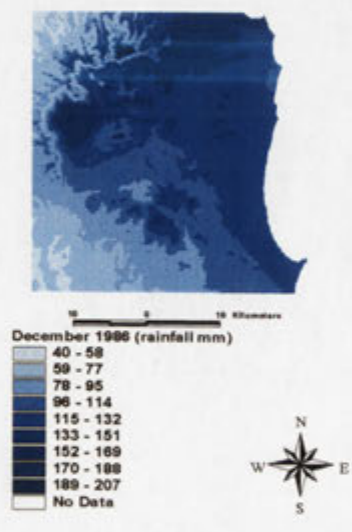

July 1986 (rainfall mm)
16 - 30
31 - 45
46 - 59
60 - 74
75 - 89
90 - 103
104 - 118
119 - 133
No Data
N
W
E
S

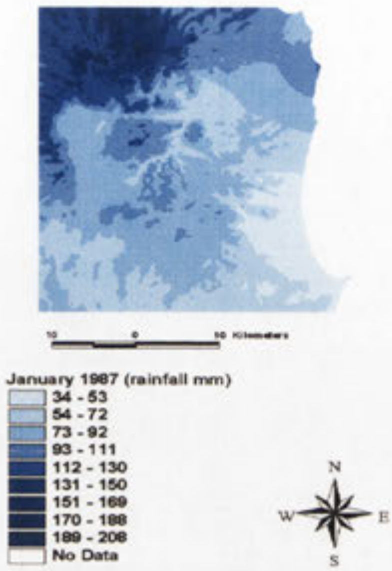

August 1986 (rainfall mm)
16 - 23
24 - 31
32 - 38
39 - 46
47 - 53
54 - 61
62 - 68
69 - 76
77 - 84
No Data
N
W
E
S

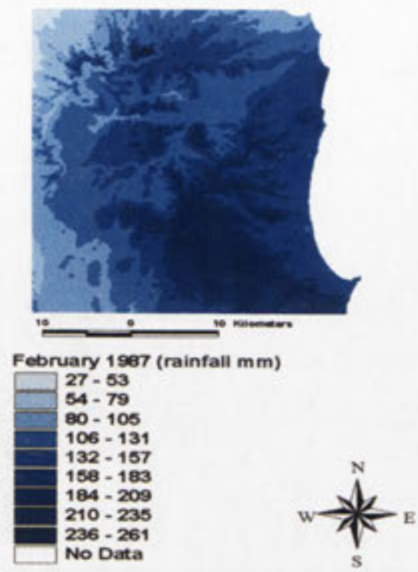

September 1986 (rainfall mm)
8 - 11
12 - 15
16 - 19
20 - 23
24 - 27
28 - 31
32 - 35
36 - 39
40 - 43
No Data
N
W
E
S

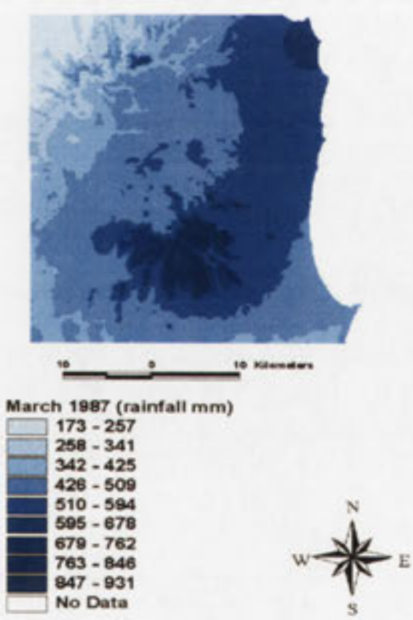

October 1986 (rainfall mm)
42 - 54
55 - 66
67 - 79
80 - 91
92 - 104
105 - 116
117 - 129
130 - 141
142 - 154
No Data
N
W
E
S

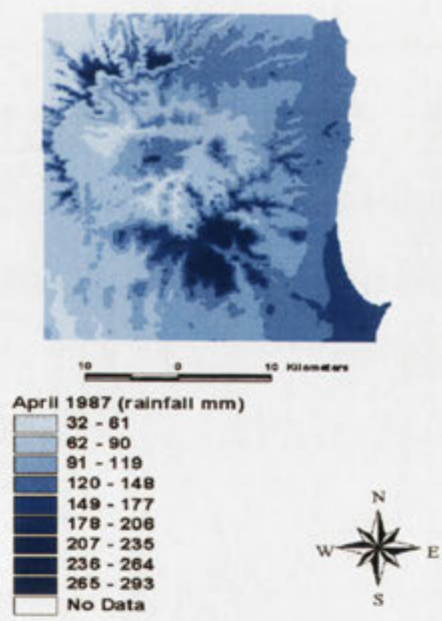

November 1986 (rainfall mm)
105 - 131
132 - 158
159 - 185
186 - 211
212 - 238
239 - 265
266 - 291
292 - 318
319 - 345
No Data
N
W
E
S


December 1986 (rainfall mm)
40 - 58
59 - 77
78 - 95
96 - 114
115 - 132
133 - 151
152 - 169
170 - 188
189 - 207
No Data
N
W
E
S


10 0 10 Kilometers
January 1987 (rainfall mm)
34 - 53
54 - 72
73 - 92
93 - 111
112 - 130
131 - 150
151 - 169
170 - 188
189 - 208
No Data
N
W
E
S


10 0 10 Kilometers
February 1987 (rainfall mm)
27 - 53
54 - 79
80 - 105
106 - 131
132 - 157
158 - 183
184 - 209
210 - 235
236 - 261
No Data
N
W
E
S


10 0 10 Kilometers
March 1987 (rainfall mm)
173 - 257
258 - 341
342 - 425
426 - 509
510 - 594
595 - 678
679 - 762
763 - 846
847 - 931
No Data
N
W
E
S


10 0 10 Kilometers
April 1987 (rainfall mm)
32 - 61
62 - 90
91 - 119
120 - 148
149 - 177
178 - 206
207 - 235
236 - 264
265 - 293
No Data
N
W
E
S

Appendix D. Monthly Rainfall Records and Major Recorded Fish Kill Events

Event	Month	M.12	M.11	M.10	M.9	M.8	M.7	M.6	M.5	M.4	M.3	M.2	M.1	Mx	Smooth	cumux
0	jan	57.00	185.00	314.00	146.00	156.00	51.00	216.00	26.00	78.00	72.00	96.00	74.00	98.00	83.89	1569.00
0	feb	185.00	314.00	146.00	156.00	51.00	216.00	26.00	78.00	72.00	96.00	74.00	98.00	14.00	85.18	1526.00
0	mar	314.00	146.00	156.00	51.00	216.00	26.00	78.00	72.00	96.00	74.00	98.00	14.00	94.00	85.34	1435.00
0	apr	146.00	156.00	51.00	216.00	26.00	78.00	72.00	96.00	74.00	98.00	14.00	94.00	75.00	83.44	1196.00
0	may	156.00	51.00	216.00	26.00	78.00	72.00	96.00	74.00	98.00	14.00	94.00	75.00	117.00	76.61	1167.00
0	jun	51.00	216.00	26.00	78.00	72.00	96.00	74.00	98.00	14.00	94.00	75.00	117.00	26.00	67.13	1037.00
0	jul	216.00	26.00	78.00	72.00	96.00	74.00	98.00	14.00	94.00	75.00	117.00	26.00	67.00	60.62	1053.00
0	aug	26.00	78.00	72.00	96.00	74.00	98.00	14.00	94.00	75.00	117.00	26.00	67.00	61.00	59.13	898.00
0	sep	78.00	72.00	96.00	74.00	98.00	14.00	94.00	75.00	117.00	26.00	67.00	61.00	15.00	66.16	887.00
0	oct	72.00	96.00	74.00	98.00	14.00	94.00	75.00	117.00	26.00	67.00	61.00	15.00	81.00	84.51	890.00
0	nov	96.00	74.00	98.00	14.00	94.00	75.00	117.00	26.00	67.00	61.00	15.00	81.00	172.00	105.50	990.00
0	dec	74.00	98.00	14.00	94.00	75.00	117.00	26.00	67.00	61.00	15.00	81.00	172.00	138.00	119.62	1032.00
0	jan	98.00	14.00	94.00	75.00	117.00	26.00	67.00	61.00	15.00	81.00	172.00	138.00	82.00	126.34	1040.00
0	feb	14.00	94.00	75.00	117.00	26.00	67.00	61.00	15.00	81.00	172.00	138.00	82.00	111.00	128.16	1053.00
1	mar	94.00	75.00	117.00	26.00	67.00	61.00	15.00	81.00	172.00	138.00	82.00	111.00	637.00	128.16	1676.00
0	apr	75.00	117.00	26.00	67.00	61.00	15.00	81.00	172.00	138.00	82.00	111.00	637.00	128.00	128.16	1710.00
0	may	117.00	26.00	67.00	61.00	15.00	81.00	172.00	138.00	82.00	111.00	637.00	128.00	376.00	126.16	2011.00
0	jun	26.00	67.00	61.00	15.00	81.00	172.00	138.00	82.00	111.00	637.00	128.00	376.00	141.00	119.26	2035.00
0	jul	67.00	61.00	15.00	81.00	172.00	138.00	82.00	111.00	637.00	128.00	376.00	141.00	72.00	109.84	2081.00
0	aug	61.00	15.00	81.00	172.00	138.00	82.00	111.00	637.00	128.00	376.00	141.00	72.00	153.00	100.11	2167.00
0	sep	15.00	81.00	172.00	138.00	82.00	111.00	637.00	128.00	376.00	141.00	72.00	153.00	0.00	88.46	2106.00
0	oct	81.00	172.00	138.00	82.00	111.00	637.00	128.00	376.00	141.00	72.00	153.00	0.00	139.00	80.08	2230.00
0	nov	172.00	138.00	82.00	111.00	637.00	128.00	376.00	141.00	72.00	153.00	0.00	139.00	24.00	92.82	2173.00
0	dec	138.00	82.00	111.00	637.00	128.00	376.00	141.00	72.00	153.00	0.00	139.00	24.00	171.00	148.82	2172.00
0	jan	82.00	111.00	637.00	128.00	376.00	141.00	72.00	153.00	0.00	139.00	24.00	171.00	434.00	232.54	2468.00
0	feb	111.00	637.00	128.00	376.00	141.00	72.00	153.00	0.00	139.00	24.00	171.00	434.00	51.00	281.86	2437.00
0	mar	637.00	128.00	376.00	141.00	72.00	153.00	0.00	139.00	24.00	171.00	434.00	51.00	345.00	268.38	2671.00
0	apr	128.00	376.00	141.00	72.00	153.00	0.00	139.00	24.00	171.00	434.00	51.00	345.00	728.00	225.79	2762.00
0	may	376.00	141.00	72.00	153.00	0.00	139.00	24.00	171.00	434.00	51.00	345.00	728.00	7.00	186.73	2641.00
0	jun	141.00	72.00	153.00	0.00	139.00	24.00	171.00	434.00	51.00	345.00	728.00	7.00	89.00	160.25	2354.00
0	jul	72.00	153.00	0.00	139.00	24.00	171.00	434.00	51.00	345.00	728.00	7.00	89.00	228.00	148.33	2441.00
0	aug	153.00	0.00	139.00	24.00	171.00	434.00	51.00	345.00	728.00	7.00	89.00	228.00	125.00	142.61	2494.00
0	sep	0.00	139.00	24.00	171.00	434.00	51.00	345.00	728.00	7.00	89.00	228.00	125.00	167.00	132.44	2508.00
0	oct	139.00	24.00	171.00	434.00	51.00	345.00	728.00	7.00	89.00	228.00	125.00	167.00	31.00	123.83	2539.00
0	nov	24.00	171.00	434.00	51.00	345.00	728.00	7.00	89.00	228.00	125.00	167.00	31.00	80.00	130.67	2480.00
0	dec	171.00	434.00	51.00	345.00	728.00	7.00	89.00	228.00	125.00	167.00	31.00	80.00	302.00	154.44	2758.00
0	jan	434.00	51.00	345.00	728.00	7.00	89.00	228.00	125.00	167.00	31.00	80.00	302.00	168.00	179.95	2755.00
0	feb	51.00	345.00	728.00	7.00	89.00	228.00	125.00	167.00	31.00	80.00	302.00	168.00	197.00	192.81	2518.00
0	mar	345.00	728.00	7.00	89.00	228.00	125.00	167.00	31.00	80.00	302.00	168.00	197.00	192.00	195.25	2659.00
0	apr	728.00	7.00	89.00	228.00	125.00	167.00	31.00	80.00	302.00	168.00	197.00	192.00	391.00	188.31	2705.00
0	may	7.00	89.00	228.00	125.00	167.00	31.00	80.00	302.00	168.00	197.00	192.00	391.00	210.00	159.07	2187.00
0	jun	89.00	228.00	125.00	167.00	31.00	80.00	302.00	168.00	197.00	192.00	391.00	210.00	68.00	111.01	2248.00
0	jul	228.00	125.00	167.00	31.00	80.00	302.00	168.00	197.00	192.00	391.00	210.00	68.00	58.00	72.48	2217.00
0	aug	125.00	167.00	31.00	80.00	302.00	168.00	197.00	192.00	391.00	210.00	68.00	58.00	80.00	57.27	2069.00
0	sep	167.00	31.00	80.00	302.00	168.00	197.00	192.00	391.00	210.00	68.00	58.00	80.00	23.00	63.93	1967.00
0	oct	31.00	80.00	302.00	168.00	197.00	192.00	391.00	210.00	68.00	58.00	80.00	23.00	51.00	102.24	1851.00
0	nov	80.00	302.00	168.00	197.00	192.00	391.00	210.00	68.00	58.00	80.00	23.00	51.00	218.00	168.65	2038.00
0	dec	302.00	168.00	197.00	192.00	391.00	210.00	68.00	58.00	80.00	23.00	51.00	218.00	265.00	235.79	2223.00
0	jan	168.00	197.00	192.00	391.00	210.00	68.00	58.00	80.00	23.00	51.00	218.00	265.00	228.00	290.52	2149.00
0	feb	197.00	192.00	391.00	210.00	68.00	58.00	80.00	23.00	51.00	218.00	265.00	228.00	402.00	331.82	2383.00
0	mar	192.00	391.00	210.00	68.00	58.00	80.00	23.00	51.00	218.00	265.00	228.00	402.00	337.00	351.23	2523.00
0	apr	391.00	210.00	68.00	58.00	80.00	23.00	51.00	218.00	265.00	228.00	402.00	337.00	348.00	333.96	2679.00
0	may	210.00	68.00	58.00	80.00	23.00	51.00	218.00	265.00	228.00	402.00	337.00	348.00	333.00	253.65	2621.00
0	jun	68.00	58.00	80.00	23.00	51.00	218.00	265.00	228.00	402.00	337.00	348.00	333.00	106.00	126.76	2517.00
0	jul	58.00	80.00	23.00	51.00	218.00	265.00	228.00	402.00	337.00	348.00	333.00	106.00	27.00	35.54	2476.00
0	aug	80.00	23.00	51.00	218.00	265.00	228.00	402.00	337.00	348.00	333.00	106.00	27.00	5.00	20.80	2423.00
0	sep	23.00	51.00	218.00	265.00	228.00	402.00	337.00	348.00	333.00	106.00	27.00	5.00	48.00	48.03	2391.00
0	oct	51.00	218.00	265.00	228.00	402.00	337.00	348.00	333.00	106.00	27.00	5.00	48.00	106.00	75.26	2474.00
0	nov	218.00	265.00	228.00	402.00	337.00	348.00	333.00	106.00	27.00	5.00	48.00	106.00	107.00	86.38	2530.00
0	dec	265.00	228.00	402.00	337.00	348.00	333.00	106.00	27.00	5.00	48.00	106.00	107.00	68.00	88.71	2380.00
0	jan	228.00	402.00	337.00	348.00	333.00	106.00	27.00	5.00	48.00	106.00	107.00	68.00	107.00	91.45	2222.00
0	feb	402.00	337.00	348.00	333.00	106.00	27.00	5.00	48.00	106.00	107.00	68.00	107.00	127.00	94.14	2121.00
0	mar	337.00	348.00	333.00	106.00	27.00	5.00	48.00	106.00	107.00	68.00	107.00	127.00	64.00	96.97	1783.00
0	apr	348.00	333.00	106.00	27.00	5.00	48.00	106.00	107.00	68.00	107.00	127.00	64.00	37.00	102.91	1483.00
1	may	333.00	106.00	27.00	5.00	48.00	106.00	107.00	68.00	107.00	127.00	64.00	37.00	262.00	109.07	1397.00
1	jun	106.00	27.00	5.00	48.00	106.00	107.00	68.00	107.00	127.00	64.00	37.00	262.00	158.00	107.30	1222.00
0	jul	27.00	5.00	48.00	106.00	107.00	68.00	107.00	127.00	64.00	37.00	262.00	158.00	158.00	93.34	1274.00
0	aug	5.00	48.00	106.00	107.00	68.00	107.00	127.00	64.00	37.00	262.00	158.00	158.00	2.00	75.31	1249.00
0	sep	48.00	106.00	107.00	68.00	107.00	127.00	64.00	37.00	262.00	158.00	158.00	2.00	0.00	68.13	1244.00
0	oct	106.00	107.00	68.00	107.00	127.00	64.00	37.00	262.00	158.00	158.00	2.00	0.00	126.00	76.50	1322.00
0	nov	107.00	68.00	107.00	127.00	64.00	37.00	262.00	158.00	158.00	2.00	0.00	126.00	47.00	96.50	1263.00
1	dec	68.00	107.00	127.00	64.00	37.00	262.00	158.00	158.00	2.00	0.00	126.00	47.00	261.00	127.68	1417.00
0	jan	107.00	127.00	64.00	37.00	262.00	158.00	158.00	2.00	0.00	126.00	47.00	261.00	78.00	162.77	1427.00
0	feb	127.00	64.00	37.00	262.00	158.00	158.00	2.00	0.00	126.00	47.00	261.00	78.00	218.00	184.42	1538.00
1	mar	64.00	37.00	262.00	158.00	158.00	2.00	0.00	126.00	47.00	261.00	78.00	218.00	287.00	185.66	1698.00
0	apr	37.00	262.00	158.00	158.00	2.00	0.00	126.00	47.00	261.00	78.00	218.00	287.00	139.00	168.10	1773.00
0	may	262.00	158.00	158.00	2.00	0.00	126.00	47.00	261.00	78.00	218.00	287.00	139.00	163.00	134.05	1899.00
0	jun	158.00	158.00	2.00	0.00	126.00	47.00	261.00	78.00	218.00	287.00	139.00	163.00	55.00	91.31	1692.00
0	jul	158.00	2.00	0.00	126.00	47.00	261.00	78.00	218.00	287.00	139.00	163.00	55.00	85.00	52.34	1619.00
0	aug	2.00	0.00	126.00	47.00	261.00	78.00	218.00	287.00	139.00	163.00	55.00	85.00	13.00	29.48	1474.00
0	sep	0.00	126.00	47.00	261.00	78.00	218.00	287.00	139.00	163.00	55.00	85.00	13.00	24.00	28.87	1496.00
0	oct	126.00	47.00	261.00	78.00	218.00	287.00	139.00	163.00	55.00	85.00	13.00	24.00	49.00	48.95	1545.00
0	nov	47.00	261.00	78.00	218.00	287.00	139.00	163.00	55.00	85.00	13.00	24.00	49.00	121.00	76.85	1540.00
0	dec	261.00	78.00	218.00	287.00	139.00	163.00	55.00	85.00	13.00	24.00	49.00	121.00	102.00	99.22	1595.00
0	jan	78.00	218.00	287.00	139.00	163.00	55.00	85.00	13.00	24.00	49.00	121.00	102.00	96.00	115.94	1430.00
0	feb	218.00	287.00	139.00	163.00	55.00	85.00	13.00	24.00	49.00	121.00	102.00	96.00	170.00	126.59	1522.00
0	mar	287.00	139.00	163.00	55.00	85.00	13.00	24.00	49.00	121.00	102.00	96.00	170.00	157.00	129.63	1461.00
0	apr	139.00	163.00	55.00	85.00	13.00	24.00	49.00	121.00	102.00	96.00	170.00	157.00	138.00	129.63	1312.00
0	may	163.00	55.00	85.00	13.00	24.00	49.00	121.00	102.00	96.00	170.00	157.00	138.00	117.00	123.95	1290.00
0	jun	55.00	85.00	13.00	24.00	49.00	121.00	102.00	96.00	170.00	157.00	138.00	117.00	41.00	106.91	1168.00
0	jul	85.00	13.00	24.00	49.00	121.00	102.00	96.00	170.00	157.00	138.00	117.00	41.00	187.00	89.87	1300.00
1	aug	13.00	24.00	49.00	121.00	102.00	96.00	170.00	157.00	138.00	117.00	41.00	187.00	70.00	86.53	1285.00
0	sep	24.00	49.00	121.00	102.00	96.00	170.00	157.00	138.00	117.00	41.00	187.00	70.00	104.00	93.56	1376.00
0	oct	49.00	121.00	102.00	96.00	170.00	157.00	138.00	117.00	41.00	187.00	70.00	104.00	101.00	105.91	1453.00
0	nov	121.00	102.00	96.00	170.00	157.00	138.00	117.00	41.00	187.00	70.00	104.00	101.00	63.00	128.75	1467.00

0	dec	102.00	96.00	170.00	157.00	138.00	117.00	41.00	187.00	70.00	104.00	101.00	63.00	180.00	159.44	1526.00
0	jan	96.00	170.00	157.00	138.00	117.00	41.00	187.00	70.00	104.00	101.00	63.00	180.00	197.00	180.17	1621.00
0	feb	170.00	157.00	138.00	117.00	41.00	187.00	70.00	104.00	101.00	63.00	180.00	197.00	174.00	183.55	1699.00
0	mar	157.00	138.00	117.00	41.00	187.00	70.00	104.00	101.00	63.00	180.00	197.00	174.00	550.00	178.05	2079.00
0	apr	138.00	117.00	41.00	187.00	70.00	104.00	101.00	63.00	180.00	197.00	174.00	550.00	105.00	159.91	2027.00
0	may	117.00	41.00	187.00	70.00	104.00	101.00	63.00	180.00	197.00	174.00	550.00	105.00	231.00	120.16	2120.00
0	jun	41.00	187.00	70.00	104.00	101.00	63.00	180.00	197.00	174.00	550.00	105.00	231.00	69.00	77.03	2072.00
0	jul	187.00	70.00	104.00	101.00	63.00	180.00	197.00	174.00	550.00	105.00	231.00	69.00	60.00	52.09	2091.00
0	aug	70.00	104.00	101.00	63.00	180.00	197.00	174.00	550.00	105.00	231.00	69.00	60.00	35.00	42.91	1939.00
0	sep	104.00	101.00	63.00	180.00	197.00	174.00	550.00	105.00	231.00	69.00	60.00	35.00	30.00	42.21	1899.00
0	oct	101.00	63.00	180.00	197.00	174.00	550.00	105.00	231.00	69.00	60.00	35.00	30.00	73.00	50.73	1868.00
0	nov	63.00	180.00	197.00	174.00	550.00	105.00	231.00	69.00	60.00	35.00	30.00	73.00	23.00	71.56	1790.00
0	dec	180.00	197.00	174.00	550.00	105.00	231.00	69.00	60.00	35.00	30.00	73.00	23.00	124.00	98.27	1851.00
0	jan	197.00	174.00	550.00	105.00	231.00	69.00	60.00	35.00	30.00	73.00	23.00	124.00	95.00	117.16	1766.00
0	feb	174.00	550.00	105.00	231.00	69.00	60.00	35.00	30.00	73.00	23.00	124.00	95.00	394.00	123.98	1963.00
0	mar	550.00	105.00	231.00	69.00	60.00	35.00	30.00	73.00	23.00	124.00	95.00	394.00	111.00	122.45	1900.00
0	apr	105.00	231.00	69.00	60.00	35.00	30.00	73.00	23.00	124.00	95.00	394.00	111.00	125.00	110.89	1475.00
0	may	231.00	69.00	60.00	35.00	30.00	73.00	23.00	124.00	95.00	394.00	111.00	125.00	101.00	89.63	1471.00
0	jun	69.00	60.00	35.00	30.00	73.00	23.00	124.00	95.00	394.00	111.00	125.00	101.00	53.00	71.12	1293.00
0	jul	60.00	35.00	30.00	73.00	23.00	124.00	95.00	394.00	111.00	125.00	101.00	53.00	2.00	61.63	1226.00
0	aug	35.00	30.00	73.00	23.00	124.00	95.00	394.00	111.00	125.00	101.00	53.00	2.00	95.00	55.25	1261.00
0	sep	30.00	73.00	23.00	124.00	95.00	394.00	111.00	125.00	101.00	53.00	2.00	95.00	18.00	56.75	1244.00
0	oct	73.00	23.00	124.00	95.00	394.00	111.00	125.00	101.00	53.00	2.00	95.00	18.00	21.00	86.96	1235.00
0	nov	23.00	124.00	95.00	394.00	111.00	125.00	101.00	53.00	2.00	95.00	18.00	21.00	226.00	145.29	1388.00
0	dec	124.00	95.00	394.00	111.00	125.00	101.00	53.00	2.00	95.00	18.00	21.00	226.00	190.00	191.09	1555.00
0	jan	95.00	394.00	111.00	125.00	101.00	53.00	2.00	95.00	18.00	21.00	226.00	190.00	225.00	200.39	1656.00
0	feb	394.00	111.00	125.00	101.00	53.00	2.00	95.00	18.00	21.00	226.00	190.00	225.00	185.00	191.12	1746.00
0	mar	111.00	125.00	101.00	53.00	2.00	95.00	18.00	21.00	226.00	190.00	225.00	185.00	149.00	182.59	1501.00
0	apr	125.00	101.00	53.00	2.00	95.00	18.00	21.00	226.00	190.00	225.00	185.00	149.00	63.00	173.39	1453.00
0	may	101.00	53.00	2.00	95.00	18.00	21.00	226.00	190.00	225.00	185.00	149.00	63.00	350.00	153.47	1678.00
0	jun	53.00	2.00	95.00	18.00	21.00	226.00	190.00	225.00	185.00	149.00	63.00	350.00	180.00	120.69	1757.00
0	jul	2.00	95.00	18.00	21.00	226.00	190.00	225.00	185.00	149.00	63.00	350.00	180.00	76.00	78.39	1780.00
0	aug	95.00	18.00	21.00	226.00	190.00	225.00	185.00	149.00	63.00	350.00	180.00	76.00	40.00	41.87	1818.00
0	sep	18.00	21.00	226.00	190.00	225.00	185.00	149.00	63.00	350.00	180.00	76.00	40.00	12.00	32.96	1735.00
0	oct	21.00	226.00	190.00	225.00	185.00	149.00	63.00	350.00	180.00	76.00	40.00	12.00	54.00	59.02	1771.00
0	nov	226.00	190.00	225.00	185.00	149.00	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	104.71	1947.00
0	dec	190.00	225.00	185.00	149.00	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	130.00	131.29	1851.00
0	jan	225.00	185.00	149.00	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	130.00	177.00	116.59	1838.00
0	feb	185.00	149.00	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	130.00	177.00	82.00	84.49	1695.00
0	mar	149.00	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	130.00	177.00	82.00	66.00	65.29	1576.00
0	apr	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	130.00	177.00	82.00	66.00	36.00	62.22	1463.00
0	may	63.00	350.00	180.00	76.00	40.00	12.00	54.00	197.00	130.00	177.00	82.00	66.00	340.00	66.36	1767.00
0	jun	180.00	76.00	40.00	12.00	54.00	197.00	130.00	177.00	82.00	66.00	36.00	340.00	63.00	71.67	1453.00
0	jul	76.00	40.00	12.00	54.00	197.00	130.00	177.00	82.00	66.00	36.00	340.00	63.00	104.00	75.17	1377.00
0	aug	40.00	12.00	54.00	197.00	130.00	177.00	82.00	66.00	36.00	340.00	63.00	104.00	8.00	77.56	1309.00
0	sep	12.00	54.00	197.00	130.00	177.00	82.00	66.00	36.00	340.00	63.00	104.00	8.00	72.00	83.19	1341.00
0	oct	54.00	197.00	130.00	177.00	82.00	66.00	36.00	340.00	63.00	104.00	8.00	72.00	106.00	95.27	1435.00
0	nov	197.00	130.00	177.00	82.00	66.00	36.00	340.00	63.00	104.00	8.00	72.00	106.00	204.00	107.47	1585.00
0	dec	130.00	177.00	82.00	66.00	36.00	340.00	63.00	104.00	8.00	72.00	106.00	204.00	129.00	112.41	1517.00
0	jan	177.00	82.00	66.00	36.00	340.00	63.00	104.00	8.00	72.00	106.00	204.00	129.00	50.00	117.86	1437.00
0	feb	82.00	66.00	36.00	340.00	63.00	104.00	8.00	72.00	106.00	204.00	129.00	50.00	107.00	132.81	1367.00
0	mar	66.00	36.00	340.00	63.00	104.00	8.00	72.00	106.00	204.00	129.00	50.00	107.00	39.00	147.77	1324.00
0	apr	36.00	340.00	63.00	104.00	8.00	72.00	106.00	204.00	129.00	50.00	107.00	39.00	313.00	152.75	1571.00
0	may	340.00	63.00	104.00	8.00	72.00	106.00	204.00	129.00	50.00	107.00	39.00	313.00	237.00	141.68	1772.00
0	jun	63.00	104.00	8.00	72.00	106.00	204.00	129.00	50.00	107.00	39.00	313.00	237.00	26.00	108.47	1458.00
0	jul	104.00	8.00	72.00	106.00	204.00	129.00	50.00	107.00	39.00	313.00	237.00	26.00	75.00	75.26	1470.00
1	aug	8.00	72.00	106.00	204.00	129.00	50.00	107.00	39.00	313.00	237.00	26.00	75.00	65.00	66.46	1431.00
0	sep	72.00	106.00	204.00	129.00	50.00	107.00	39.00	313.00	237.00	26.00	75.00	65.00	215.00	77.51	1638.00
0	oct	106.00	204.00	129.00	50.00	107.00	39.00	313.00	237.00	26.00	75.00	65.00	215.00	33.00	96.99	1599.00
0	nov	204.00	129.00	50.00	107.00	39.00	313.00	237.00	26.00	75.00	65.00	215.00	33.00	125.00	120.04	1618.00
0	dec	129.00	50.00	107.00	39.00	313.00	237.00	26.00	75.00	65.00	215.00	33.00	125.00	154.00	164.66	1568.00
0	jan	50.00	107.00	39.00	313.00	237.00	26.00	75.00	65.00	215.00	33.00	125.00	154.00	341.00	237.14	1780.00
0	feb	107.00	39.00	313.00	237.00	26.00	75.00	65.00	215.00	33.00	125.00	154.00	341.00	255.00	294.48	1985.00
0	mar	39.00	313.00	237.00	26.00	75.00	65.00	215.00	33.00	125.00	154.00	341.00	255.00	346.00	309.36	2224.00
0	apr	313.00	237.00	26.00	75.00	65.00	215.00	33.00	125.00	154.00	341.00	255.00	346.00	269.00	299.14	2454.00
0	may	237.00	26.00	75.00	65.00	215.00	33.00	125.00	154.00	341.00	255.00	346.00	269.00	150.00	275.57	2291.00
0	jun	26.00	75.00	65.00	215.00	33.00	125.00	154.00	341.00	255.00	346.00	269.00	150.00	494.00	236.17	2548.00
0	jul	75.00	65.00	215.00	33.00	125.00	154.00	341.00	255.00	346.00	269.00	150.00	494.00	254.00	197.89	2776.00
0	aug	65.00	215.00	33.00	125.00	154.00	341.00	255.00	346.00	269.00	150.00	494.00	254.00	122.00	181.66	2823.00
0	sep	215.00	33.00	125.00	154.00	341.00	255.00	346.00	269.00	150.00	494.00	254.00	122.00	51.00	179.59	2809.00
0	oct	33.00	125.00	154.00	341.00	255.00	346.00	269.00	150.00	494.00	254.00	122.00	51.00	265.00	179.94	2859.00
0	nov	125.00	154.00	341.00	255.00	346.00	269.00	150.00	494.00	254.00	122.00	51.00	265.00	178.00	181.59	3004.00
0	dec	154.00	341.00	255.00	346.00	269.00	150.00	494.00	254.00	122.00	51.00	265.00	178.00	136.00	181.38	3015.00
0	jan	341.00	255.00	346.00	269.00	150.00	494.00	254.00	122.00	51.00	265.00	178.00	136.00	193.00	177.32	3054.00
0	feb	255.00	346.00	269.00	150.00	494.00	254.00	122.00	51.00	265.00	178.00	136.00	193.00	219.00	165.18	2932.00
0	mar	346.00	269.00	150.00	494.00	254.00	122.00	51.00	265.00	178.00	136.00	193.00	219.00	126.00	141.97	2803.00
0	apr	269.00	150.00	494.00	254.00	122.00	51.00	265.00	178.00	136.00	193.00	219.00	126.00	124.00	118.18	2581.00
0	may	150.00	494.00	254.00	122.00	51.00	265.00	178.00	136.00	193.00	219.00	126.00	124.00	66.00	94.10	2378.00
0	jun	494.00	254.00	122.00	51.00	265.00	178.00	136.00	193.00	219.00	126.00	124.00	66.00	196.00	59.80	2424.00
0	jul	254.00	122.00	51.00	265.00	178.00	136.00	193.00	219.00	126.00	124.00	66.00	196.00	26.00	27.00	1956.00
0	aug	122.00	51.00	265.00	178.00	136.00	193.00	219.00	126.00	124.00	66.00	196.00	26.00	18.00	18.40	1720.00
0	sep	51.00	265.00	178.00	136.00	193.00	219.00	126.00	124.00	66.00	196.00	26.00	18.00	11.00	43.34	1609.00
0	oct	265.00	178.00	136.00	193.00	219.00	126.00	124.00	66.00	196.00	26.00	18.00	11.00	126.00	89.49	1684.00
0	nov	178.00	136.00	193.00	219.00	126.00	124.00	66.00	196.00	26.00	18.00	11.00	126.00	203.00	137.40	1622.00
0	dec	136.00	193.00	219.00	126.00	124.00	66.00	196.00	26.00	18.00	11.00	126.00	203.00	125.00	183.72	1569.00

Appendix E. Drainage Costs Analysis

Costing for Minimum Drainage Density

LENGTH	WIDTH	DEPTH	DIMENSIONS	A	B	C	D	E	F	Total
385.900	4	1.0	1543.6	12.3	77.2	7718		1458		9265.4
443.749	3	1.0	1331.247	10.6	66.6	6656		1257		7990.7
372.558	2	1.0	745.116	6.0	37.3	3726		704		4472.5
305.679	2	0.5	305.679	2.4	30.6	1528		289		1850.1
799.421	3	1.0	2398.263	19.2	119.9	11991		2265		14395.4
321.227	3	1.0	963.681	7.7	48.2	4818		910		5784.4
271.957	2	1.0	543.914	4.4	27.2	2720		514		3264.8
139.796	3	1.0	419.388	3.4	21.0	2097		396		2517.4
415.146	2	1.0	830.292	6.6	41.5	4151		784		4983.8
135.630	2	1.0	271.26	2.2	13.6	1356		256		1628.2
395.270	3	1.0	1185.81	9.5	59.3	5929		1120		7117.8
3.869	6	2.0	46.428	0.4	1.2	232		44		277.5
183.836	2	1.0	367.672	2.9	18.4	1838		347		2206.9
315.862	2	1.0	631.724	5.1	31.6	3159		597		3791.9
380.805	3	1.0	1142.415	9.1	57.1	5712		1079		6857.3
817.995	2	1.0	1635.99	13.1	81.8	8180		1545		9819.9
142.575	3	1.0	427.725	3.4	21.4	2139		404		2567.4
459.208	3	1.0	1377.624	11.0	68.9	6888		1301		8269.1
154.800	2	1.0	309.6	2.5	15.5	1548		292		1858.4
25.645	3	1.0	76.935	0.6	3.8	385		73		461.8
303.262	3	1.0	909.786	7.3	45.5	4549		859		5460.9
138.577	3	2.0	831.462	6.7	20.8	4157		785		4970.0
291.902	3	2.0	1751.412	14.0	43.8	8757		1654		10469.0
386.964	3	2.0	2321.784	18.6	58.0	11609		2193		13878.3
123.505	3	2.0	741.03	5.9	18.5	3705		700		4429.5
373.530	3	1.0	1120.59	9.0	56.0	5603		1058		6726.3
143.647	3	1.0	430.941	3.4	21.5	2155		407		2586.7
223.351	2	1.0	446.702	3.6	22.3	2234		422		2681.3
168.931	3	1.0	506.793	4.1	25.3	2534		479		3042.0
159.808	5	2.0	1598.08	12.8	40.0	7990		1509		9552.4
709.677	2	1.0	1419.354	11.4	71.0	7097		1341		8519.6
331.006	2	1.0	662.012	5.3	33.1	3310		625		3973.7
150.012	2	1.0	300.024	2.4	15.0	1500		283		1800.9
250.894	2	1.0	501.788	4.0	25.1	2509		474		3012.0
518.464	2	1.0	1036.928	8.3	51.8	5185		979		6224.1
197.046	3	1.0	591.138	4.7	29.6	2956		558		3548.3
6.631	5	2.0	66.31	0.5	1.7	332		63		396.4
47.655	3	1.0	142.965	1.1	7.1	715		135		858.1
293.642	2	1.0	587.284	4.7	29.4	2936		555		3525.1
278.870	3	1.0	836.61	6.7	41.8	4183		790		5021.7
342.628	4	1.0	1370.512	11.0	68.5	6853		1294		8226.4
271.564	3	2.0	1629.384	13.0	40.7	8147		1539		9739.6
808.647	6	2.0	9703.764	77.6	242.6	48519		9165		58003.7
202.267	6	2.0	2427.204	19.4	60.7	12136		2292		14508.5
258.122	5	2.0	2581.22	20.6	64.5	12906		2438		15429.1
300.989	3	2.0	1805.934	14.4	45.1	9030		1706		10794.9
156.113	2	1.0	312.226	2.5	15.6	1561		295		1874.1
36.725	2	1.0	73.45	0.6	3.7	367		69		440.9
217.640	2	1.0	435.28	3.5	21.8	2176		411		2612.7
348.685	3	1.0	1046.055	8.4	52.3	5230		988		6278.9
297.020	4	2.0	2376.16	19.0	59.4	11881		2244		14203.4
166.325	2	1.0	332.65	2.7	16.6	1663		314		1996.7
118.883	5	2.0	1188.83	9.5	29.7	5944		1123		7106.2
267.898	11	2.0	5893.756	47.2	147.3		5566	5566	7203	5760.8
323.033	3	1.0	969.099	7.8	48.5	4845		915		5817.0
326.405	2	1.0	652.81	5.2	32.6	3264		617		3918.5
50.293	3	1.0	150.879	1.2	7.5	754		142		905.6
150.728	4	2.0	1205.824	9.6	30.1	6029		1139		7207.7
140.607	4	2.0	1124.856	9.0	28.1	5624		1062		6723.8
417.438	3	2.0	2504.628	20.0	62.6	12523		2365		14971.3
143.654	4	2.0	1149.232	9.2	28.7	5746		1085		6869.5
157.622	4	2.0	1260.976	10.1	31.5	6305		1191		7537.4
51.809	4	2.0	414.472	3.3	10.4	2072		391		2477.5
32.388	4	2.0	259.104	2.1	6.5	1296		245		1548.8
27.989	4	2.0	223.912	1.8	5.6	1120		211		1338.4
45.418	4	2.0	363.344	2.9	9.1	1817		343		2171.9
147.560	6	2.0	1770.72	14.2	44.3	8854		1672		10584.4
291.018	11	2.0	6402.396	51.2	160.1		6047	6047	7825	6258.0
509.390	5	2.0	5093.9	40.8	127.3	25470		4811		30448.5

58.181	2	1.0	116.362	0.9	5.8	582		110		698.5
114.752	2	1.0	229.504	1.8	11.5	1148		217		1377.6
144.031	4	2.0	1152.248	9.2	28.8	5761		1088		6887.5
102.647	4	2.0	821.176	6.6	20.5	4106		776		4908.5
491.376	12	2.0	11793.024	94.3	294.8		11138	11138	14414	11527.0
82.231	4	2.0	657.848	5.3	16.4	3289		621		3932.2
280.171	3	2.0	1681.026	13.4	42.0	8405		1588		10048.2
23.988	11	2.0	527.736	4.2	13.2		498	498	645	515.8
58.931	12	2.0	1414.344	11.3	35.4		1336	1336	1729	1382.4
522.465	4	1.0	2089.86	16.7	104.5	10449		1974		12544.3
111.557	6	2.0	1338.684	10.7	33.5	6693		1264		8001.9
638.948	1	0.5	319.474	2.6	31.9	1597		302		1933.6
31.730	14	2.0	888.44	7.1	22.2		839	839	1086	868.4
61.592	14	2.0	1724.576	13.8	43.1		1629	1629	2108	1685.7
196.148	4	1.0	784.592	6.3	39.2	3923		741		4709.5
200.429	14	2.0	5612.012	44.9	140.3		5300	5300	6859	5485.4
197.255	5	2.0	1972.55	15.8	49.3	9863		1863		11790.8
438.728	3	1.0	1316.184	10.5	65.8	6581		1243		7900.3
358.444	1	0.5	179.222	1.4	17.9	896		169		1084.7
317.073	4	1.0	1268.292	10.1	63.4	6341		1198		7612.9
336.103	2	1.0	672.206	5.4	33.6	3361		635		4034.9
238.380	3	1.0	715.14	5.7	35.8	3576		675		4292.6
7.492	36	2.0	539.424	4.3	13.5		509	509	659	527.3
314.722	2	1.0	629.444	5.0	31.5	3147		594		3778.2
50.629	6	2.0	607.548	4.9	15.2	3038		574		3631.6
391.710	2	1.0	783.42	6.3	39.2	3917		740		4702.4
227.524	3	1.0	682.572	5.5	34.1	3413		645		4097.1
158.401	2	1.0	316.802	2.5	15.8	1584		299		1901.6
336.160	4	1.0	1344.64	10.8	67.2	6723		1270		8071.1
166.690	4	1.0	666.76	5.3	33.3	3334		630		4002.2
137.030	1	1.0	137.03	1.1	6.9	685		129		822.5
194.486	2	1.0	388.972	3.1	19.4	1945		367		2334.8
185.443	2	1.0	370.886	3.0	18.5	1854		350		2226.2
225.946	2	1.0	451.892	3.6	22.6	2259		427		2712.5
85.748	2	1.0	171.496	1.4	8.6	857		162		1029.4
49.700	2	1.0	99.4	0.8	5.0	497		94		596.6
50.331	2	1.0	100.662	0.8	5.0	503		95		604.2
38.938	2	1.0	77.876	0.6	3.9	389		74		467.4
170.269	5	2.0	1702.69	13.6	42.6	8513		1608		10177.7
48.980	3	1.0	146.94	1.2	7.3	735		139		882.0
238.921	4	1.0	955.684	7.6	47.8	4778		903		5736.4
189.960	3	2.0	1139.76	9.1	28.5	5699		1076		6812.9
88.885	2	1.0	177.77	1.4	8.9	889		168		1067.1
93.209	2	1.0	186.418	1.5	9.3	932		176		1119.0
313.055	3	1.0	939.165	7.5	47.0	4696		887		5637.3
323.053	4	1.0	1292.212	10.3	64.6	6461		1220		7756.4
228.246	4	1.0	912.984	7.3	45.6	4565		862		5480.1
133.711	4	1.0	534.844	4.3	26.7	2674		505		3210.4
183.639	4	1.0	734.556	5.9	36.7	3673		694		4409.1
159.217	1	0.5	79.6085	0.6	8.0	398		75		481.8
124.372	2	1.0	248.744	2.0	12.4	1244		235		1493.1
483.395	3	1.0	1450.185	11.6	72.5	7251		1370		8704.7
561.240	1	1.0	561.24	4.5	28.1	2806		530		3368.8
341.650	2	1.0	683.3	5.5	34.2	3417		645		4101.5
76.752	2	1.0	153.504	1.2	7.7	768		145		921.4
174.637	2	1.0	349.274	2.8	17.5	1746		330		2096.5
237.677	4	2.0	1901.416	15.2	47.5	9507		1796		11365.6
94.757	4	1.0	379.028	3.0	19.0	1895		358		2275.1
223.826	4	1.0	895.304	7.2	44.8	4477		846		5374.0
276.006	3	1.0	828.018	6.6	41.4	4140		782		4970.1
202.472	4	2.0	1619.776	13.0	40.5	8099		1530		9682.1
137.341	4	2.0	1098.728	8.8	27.5	5494		1038		6567.6
478.891	2	1.0	957.782	7.7	47.9	4789		905		5749.0
92.553	4	2.0	740.424	5.9	18.5	3702		699		4425.8
106.933	4	2.0	855.464	6.8	21.4	4277		808		5113.5
311.251	2	1.0	622.502	5.0	31.1	3113		588		3736.5
218.275	2	1.0	436.55	3.5	21.8	2183		412		2620.4
84.925	4	2.0	679.4	5.4	17.0	3397		642		4061.1
244.067	5	2.0	2440.67	19.5	61.0	12203		2305		14589.0
277.935	2	1.0	555.87	4.4	27.8	2779		525		3336.6
272.327	2	1.0	544.654	4.4	27.2	2723		514		3269.3
324.911	3	2.0	1949.466	15.6	48.7	9747		1841		11652.8
266.453	3	2.0	1598.718	12.8	40.0	7994		1510		9556.2

675.448	5	2.0	6754.48	54.0	168.9	33772		6379		40374.5
39.012	3	2.0	234.072	1.9	5.9	1170		221		1399.2
314.380	6	2.0	3772.56	30.2	94.3	18863		3563		22550.3
105.209	3	2.0	631.254	5.1	15.8	3156		596		3773.3
81.406	4	2.0	651.248	5.2	16.3	3256		615		3892.8
221.592	3	1.0	664.776	5.3	33.2	3324		628		3990.3
89.998	2	1.0	179.996	1.4	9.0	900		170		1080.4
125.904	2	1.0	251.808	2.0	12.6	1259		238		1511.5
112.682	2	1.0	225.364	1.8	11.3	1127		213		1352.7
119.548	3	2.0	717.288	5.7	17.9	3586		677		4287.5
40.933	2	1.0	81.866	0.7	4.1	409		77		491.4
507.557	5	2.0	5075.57	40.6	126.9	25378		4794		30338.9
153.541	2	1.0	307.082	2.5	15.4	1535		290		1843.2
203.915	3	2.0	1223.49	9.8	30.6	6117		1156		7313.3
78.654	2	1.0	157.308	1.3	7.9	787		149		944.2
84.795	2	1.0	169.59	1.4	8.5	848		160		1018.0
18.694	2	1.0	37.388	0.3	1.9	187		35		224.4
126.820	2	1.0	253.64	2.0	12.7	1268		240		1522.5
74.264	2	1.0	148.528	1.2	7.4	743		140		891.5
213.211	2	1.0	426.422	3.4	21.3	2132		403		2559.6
265.220	3	1.0	795.66	6.4	39.8	3978		751		4775.9
245.885	2	1.0	491.77	3.9	24.6	2459		464		2951.8
145.285	2	1.0	290.57	2.3	14.5	1453		274		1744.1
150.569	2	1.0	301.138	2.4	15.1	1506		284		1807.6
282.243	6	2.0	3386.916	27.1	84.7	16935		3199		20245.1
157.780	3	2.0	946.68	7.6	23.7	4733		894		5658.7
134.722	3	2.0	808.332	6.5	20.2	4042		763		4831.8
101.799	16	2.0	3257.568	26.1	81.4		3077	3077	3981	3184.1
155.948	2	1.0	311.896	2.5	15.6	1559		295		1872.1
106.419	2	1.0	212.838	1.7	10.6	1064		201		1277.5
493.131	4	1.0	1972.524	15.8	98.6	9863		1863		11840.0
160.017	2	1.0	320.034	2.6	16.0	1600		302		1921.0
237.864	2	1.0	475.728	3.8	23.8	2379		449		2855.5
258.830	2	1.0	517.66	4.1	25.9	2588		489		3107.2
256.990	2	1.0	513.98	4.1	25.7	2570		485		3085.1
164.752	2	1.0	329.504	2.6	16.5	1648		311		1977.8
199.564	2	1.0	399.128	3.2	20.0	1996		377		2395.7
107.322	2	1.0	214.644	1.7	10.7	1073		203		1288.4
71.237	2	1.0	142.474	1.1	7.1	712		135		855.2
228.405	2	1.0	456.81	3.7	22.8	2284		431		2742.0
243.656	2	1.0	487.312	3.9	24.4	2437		460		2925.1
162.548	3	2.0	975.288	7.8	24.4	4876		921		5829.7
353.295	11	2.0	7772.49	62.2	194.3		7341	7341	9500	7597.2
368.717	5	2.0	3687.17	29.5	92.2	18436		3482		22039.9
341.074	3	2.0	2046.444	16.4	51.2	10232		1933		12232.5
386.254	6	2.0	4635.048	37.1	115.9	23175		4378		27705.7
251.295	2	1.0	502.59	4.0	25.1	2513		475		3016.8
77.867	14	2.0	2180.276	17.4	54.5		2059	2059	2665	2131.1
95.522	2	1.0	191.044	1.5	9.6	955		180		1146.7
190.223	2	1.0	380.446	3.0	19.0	1902		359		2283.6
89.224	1	0.5	44.612	0.4	4.5	223		42		270.0
338.426	3	1.0	1015.278	8.1	50.8	5076		959		6094.1
73.823	5	2.0	738.23	5.9	18.5	3691		697		4412.7
93.214	11	2.0	2050.708	16.4	51.3		1937	1937	2506	2004.5
280.104	5	2.0	2801.04	22.4	70.0	14005		2645		16743.1
45.613	2	1.0	91.226	0.7	4.6	456		86		547.6
154.178	3	2.0	925.068	7.4	23.1	4625		874		5529.5
95.500	2	1.0	191	1.5	9.6	955		180		1146.5
218.253	4	1.0	873.012	7.0	43.7	4365		825		5240.2
608.612	5	1.0	3043.06	24.3	152.2	15215		2874		18265.8
453.415	1	1.0	453.415	3.6	22.7	2267		428		2721.6
390.018	5	2.0	3900.18	31.2	97.5	19501		3684		23313.1
306.794	2	1.0	613.588	4.9	30.7	3068		579		3683.0
72.135	1	1.0	72.135	0.6	3.6	361		68		433.0
254.473	4	2.0	2035.784	16.3	50.9	10179		1923		12168.8
124.929	4	2.0	999.432	8.0	25.0	4997		944		5974.0
112.266	3	2.0	673.596	5.4	16.8	3368		636		4026.4
110.638	6	2.0	1327.656	10.6	33.2	6638		1254		7936.0
77.838	6	2.0	934.056	7.5	23.4	4670		882		5583.3
116.630	3	2.0	699.78	5.6	17.5	3499		661		4182.9
140.451	5	2.0	1404.51	11.2	35.1	7023		1326		8395.4
89.828	2	1.0	179.656	1.4	9.0	898		170		1078.4
55.041	2	1.0	110.082	0.9	5.5	550		104		660.8

167.628	3	2.0	1005.768	8.0	25.1	5029		950		6011.9
205.054	2	1.0	410.108	3.3	20.5	2051		387		2461.7
121.195	2	1.0	242.39	1.9	12.1	1212		229		1454.9
365.601	2	1.0	731.202	5.8	36.6	3656		691		4389.0
351.302	2	1.0	702.604	5.6	35.1	3513		664		4217.3
414.071	3	1.0	1242.213	9.9	62.1	6211		1173		7456.3
441.072	3	1.0	1323.216	10.6	66.2	6616		1250		7942.5
357.271	2	1.0	714.542	5.7	35.7	3573		675		4289.0
256.678	6	2.0	3080.136	24.6	77.0	15401		2909		18411.3
427.901	4	2.0	3423.208	27.4	85.6	17116		3233		20462.0
336.100	3	1.0	1008.3	8.1	50.4	5042		952		6052.3
185.194	11	2.0	4074.268	32.6	101.9		3848	3848	4980	3982.4
412.916	3	1.0	1238.748	9.9	61.9	6194		1170		7435.5
331.018	4	2.0	2648.144	21.2	66.2	13241		2501		15829.1
392.203	2	1.0	784.406	6.3	39.2	3922		741		4708.4
511.540	3	2.0	3069.24	24.6	76.7	15346		2899		18346.2
120.471	4	2.0	963.768	7.7	24.1	4819		910		5760.9
403.178	2	1.0	806.356	6.5	40.3	4032		762		4840.1
145.036	3	2.0	870.216	7.0	21.8	4351		822		5201.7
405.711	2	1.0	811.422	6.5	40.6	4057		766		4870.5
136.354	4	2.0	1090.832	8.7	27.3	5454		1030		6520.4
267.878	2	1.0	535.756	4.3	26.8	2679		506		3215.8
75.236	4	2.0	601.888	4.8	15.0	3009		568		3597.8
295.480	3	1.0	886.44	7.1	44.3	4432		837		5320.8
491.742	4	2.0	3933.936	31.5	98.3	19670		3715		23514.9
121.279	2	1.0	242.558	1.9	12.1	1213		229		1455.9
231.793	2	1.0	463.586	3.7	23.2	2318		438		2782.6
198.997	3	1.0	596.991	4.8	29.8	2985		564		3583.4
163.447	3	1.0	490.341	3.9	24.5	2452		463		2943.2
45.610	2	1.0	91.22	0.7	4.6	456		86		547.5
296.670	6	2.0	3560.04	28.5	89.0	17800		3362		21279.9
139.300	6	2.0	1671.6	13.4	41.8	8358		1579		9991.9
199.333	3	2.0	1195.998	9.6	29.9	5980		1130		7149.0
198.702	3	2.0	1192.212	9.5	29.8	5961		1126		7126.4
304.816	3	2.0	1828.896	14.6	45.7	9144		1727		10932.1
109.587	3	1.0	328.761	2.6	16.4	1644		310		1973.4
141.236	3	1.0	423.708	3.4	21.2	2119		400		2543.3
54.622	3	1.0	163.866	1.3	8.2	819		155		983.6
260.250	2	1.0	520.5	4.2	26.0	2603		492		3124.3
305.152	4	2.0	2441.216	19.5	61.0	12206		2306		14592.2
60.358	2	1.0	120.716	1.0	6.0	604		114		724.6
550.305	3	1.0	1650.915	13.2	82.5	8255		1559		9909.5
249.028	3	1.0	747.084	6.0	37.4	3735		706		4484.3
90.439	2	1.0	180.878	1.4	9.0	904		171		1085.7
665.222	5	2.0	6652.22	53.2	166.3	33261		6283		39763.3
539.105	5	2.0	5391.05	43.1	134.8	26955		5092		32224.7
136.257	2	1.0	272.514	2.2	13.6	1363		257		1635.8
70.515	3	1.0	211.545	1.7	10.6	1058		200		1269.8
301.174	3	2.0	1807.044	14.5	45.2	9035		1707		10801.5
328.486	6	2.0	3941.832	31.5	98.5	19709		3723		23562.1
48.358	4	1.0	193.432	1.5	9.7	967		183		1161.1
116.410	3	2.0	698.46	5.6	17.5	3492		660		4175.0
31.709	4	2.0	253.672	2.0	6.3	1268		240		1516.3
235.764	4	2.0	1886.112	15.1	47.2	9431		1781		11274.1
53.142	4	2.0	425.136	3.4	10.6	2126		402		2541.2
63.657	2	1.0	127.314	1.0	6.4	637		120		764.2
267.496	6	2.0	3209.952	25.7	80.2	16050		3032		19187.3
194.616	2	1.0	389.232	3.1	19.5	1946		368		2336.3
217.876	2	1.0	435.752	3.5	21.8	2179		412		2615.6
313.836	2	1.0	627.672	5.0	31.4	3138		593		3767.6
302.865	3	2.0	1817.19	14.5	45.4	9086		1716		10862.2
27.800	11	2.0	611.6	4.9	15.3		578	578	748	597.8
64.648	11	2.0	1422.256	11.4	35.6		1343	1343	1738	1390.2
221.477	6	2.0	2657.724	21.3	66.4	13289		2510		15886.4
436.392	3	1.0	1309.176	10.5	65.5	6546		1236		7858.3
			337671.7795	$2,701.37	$10,983.4	$1,407,535	$53,045	$318,912	$68,646	$1,861,822.09

A= Lime Treatment of Water (Assuming the drain is holding 10% of its depth capacity)
B=Lime Treatment of Drain Basin (Allowing for 2m buffer (1m either side of drain) at a lime application rate of 5T/Ha
C=Lime Treatment of Fill Material
D=Excavator Hire (Eh) 720 m3 per day @ %680 per day
E= Grader Hire (Gh) 720m3 per day @ $680 per day
F=Truck Hire (Th) 720 m3 per day @ $880 per day

Costing for 25% Drainage Density

LENGTH	WIDTH	DEPTH	DIMENSIONS	A	B	C	D	E	F
443.749	3	1.0	1331.247	10.6	66.6	6656		1257	
372.558	2	1.0	745.116	6.0	37.3	3726		704	
305.679	2	0.5	305.679	2.4	30.6	1528		289	
321.227	3	1.0	963.681	7.7	48.2	4818		910	
271.957	2	1.0	543.914	4.4	27.2	2720		514	
415.146	2	1.0	830.292	6.6	41.5	4151		784	
135.630	2	1.0	271.26	2.2	13.6	1356		256	
3.869	6	2.0	46.428	0.4	1.2	232		44	C
183.836	2	1.0	367.672	2.9	18.4	1838		347	
315.862	2	1.0	631.724	5.1	31.6	3159		597	
380.805	3	1.0	1142.415	9.1	57.1	5712		1079	
817.995	2	1.0	1635.99	13.1	81.8	8180		1545	
154.800	2	1.0	309.6	2.5	15.5	1548		292	
25.645	3	1.0	76.935	0.6	3.8	385		73	
138.577	3	2.0	831.462	6.7	20.8	4157		785	
291.902	3	2.0	1751.412	14.0	43.8	8757		1654	
386.964	3	2.0	2321.784	18.6	58.0	11609		2193	
373.530	3	1.0	1120.59	9.0	56.0	5603		1058	
143.647	3	1.0	430.941	3.4	21.5	2155		407	
223.351	2	1.0	446.702	3.6	22.3	2234		422	
709.677	2	1.0	1419.354	11.4	71.0	7097		1341	
331.006	2	1.0	662.012	5.3	33.1	3310		625	
150.012	2	1.0	300.024	2.4	15.0	1500		283	
250.894	2	1.0	501.788	4.0	25.1	2509		474	
518.464	2	1.0	1036.928	8.3	51.8	5185		979	
197.046	3	1.0	591.138	4.7	29.6	2956		558	
47.655	3	1.0	142.965	1.1	7.1	715		135	
293.642	2	1.0	587.284	4.7	29.4	2936		555	
278.870	3	1.0	836.61	6.7	41.8	4183		790	
342.628	4	1.0	1370.512	11.0	68.5	6853		1294	
808.647	6	2.0	9703.764	77.6	242.6	48519		9165	
300.989	3	2.0	1805.934	14.4	45.1	9030		1706	
156.113	2	1.0	312.226	2.5	15.6	1561		295	
217.640	2	1.0	435.28	3.5	21.8	2176		411	
348.685	3	1.0	1046.055	8.4	52.3	5230		988	
297.020	4	2.0	2376.16	19.0	59.4	11881		2244	
166.325	2	1.0	332.65	2.7	16.6	1663		314	
326.405	2	1.0	652.81	5.2	32.6	3264		617	
50.293	3	1.0	150.879	1.2	7.5	754		142	
150.728	4	2.0	1205.824	9.6	30.1	6029		1139	B
140.607	4	2.0	1124.856	9.0	28.1	5624		1062	B
417.438	3	2.0	2504.628	20.0	62.6	12523		2365	C
143.654	4	2.0	1149.232	9.2	28.7	5746		1085	B
157.622	4	2.0	1260.976	10.1	31.5	6305		1191	B
147.560	6	2.0	1770.72	14.2	44.3	8854		1672	B
291.018	11	2.0	6402.396	51.2	160.1		6047	6047	7825 B
509.390	5	2.0	5093.9	40.8	127.3	25470		4811	C
144.031	4	2.0	1152.248	9.2	28.8	5761		1088	
102.647	4	2.0	821.176	6.6	20.5	4106		776	
491.376	12	2.0	11793.024	94.3	294.8		11138	11138	14414 C
82.231	4	2.0	657.848	5.3	16.4	3289		621	
280.171	3	2.0	1681.026	13.4	42.0	8405		1588	
23.988	11	2.0	527.736	4.2	13.2		498	498	645 B
58.931	12	2.0	1414.344	11.3	35.4		1336	1336	1729 C
522.465	4	1.0	2089.86	16.7	104.5	10449		1974	
111.557	6	2.0	1338.684	10.7	33.5	6693		1264	C
638.948	1	0.5	319.474	2.6	31.9	1597		302	
31.730	14	2.0	888.44	7.1	22.2		839	839	1086
61.592	14	2.0	1724.576	13.8	43.1		1629	1629	2108
196.148	4	1.0	784.592	6.3	39.2	3923		741	
200.429	14	2.0	5612.012	44.9	140.3		5300	5300	6859
197.255	5	2.0	1972.55	15.8	49.3	9863		1863	
438.728	3	1.0	1316.184	10.5	65.8	6581		1243	
358.444	1	0.5	179.222	1.4	17.9	896		169	
317.073	4	1.0	1268.292	10.1	63.4	6341		1198	
336.103	2	1.0	672.206	5.4	33.6	3361		635	
238.380	3	1.0	715.14	5.7	35.8	3576		675	
314.722	2	1.0	629.444	5.0	31.5	3147		594	
391.710	2	1.0	783.42	6.3	39.2	3917		740	
227.524	3	1.0	682.572	5.5	34.1	3413		645	

158.401	2	1.0	316.802	2.5	15.8	1584		299	
336.160	4	1.0	1344.64	10.8	67.2	6723		1270	
166.690	4	1.0	666.76	5.3	33.3	3334		630	
137.030	1	1.0	137.03	1.1	6.9	685		129	
194.486	2	1.0	388.972	3.1	19.4	1945		367	
185.443	2	1.0	370.886	3.0	18.5	1854		350	
75.872	7	2.0	1062.208	8.5	26.6		1003	1003	1298 D
85.748	2	1.0	171.496	1.4	8.6	857		162	
49.700	2	1.0	99.4	0.8	5.0	497		94	
48.980	3	1.0	146.94	1.2	7.3	735		139	
238.921	4	1.0	955.684	7.6	47.8	4778		903	
189.960	3	2.0	1139.76	9.1	28.5	5699		1076	
88.885	2	1.0	177.77	1.4	8.9	889		168	
313.055	3	1.0	939.165	7.5	47.0	4696		887	B
323.053	4	1.0	1292.212	10.3	64.6	6461		1220	
228.246	4	1.0	912.984	7.3	45.6	4565		862	
133.711	4	1.0	534.844	4.3	26.7	2674		505	
183.639	4	1.0	734.556	5.9	36.7	3673		694	
483.395	3	1.0	1450.185	11.6	72.5	7251		1370	
39.500	7	2.0	553	4.4	13.8		522	522	676 D
561.240	1	1.0	561.24	4.5	28.1	2806		530	
76.752	2	1.0	153.504	1.2	7.7	768		145	
174.637	2	1.0	349.274	2.8	17.5	1746		330	
237.677	4	2.0	1901.416	15.2	47.5	9507		1796	
94.757	4	1.0	379.028	3.0	19.0	1895		358	
223.826	4	1.0	895.304	7.2	44.8	4477		846	
137.341	4	2.0	1098.728	8.8	27.5	5494		1038	
478.891	2	1.0	957.782	7.7	47.9	4789		905	
106.933	4	2.0	855.464	6.8	21.4	4277		808	C
311.251	2	1.0	622.502	5.0	31.1	3113		588	
218.275	2	1.0	436.55	3.5	21.8	2183		412	
277.935	2	1.0	555.87	4.4	27.8	2779		525	
272.327	2	1.0	544.654	4.4	27.2	2723		514	
266.453	3	2.0	1598.718	12.8	40.0	7994		1510	
675.448	5	2.0	6754.48	54.0	168.9	33772		6379	
221.592	3	1.0	664.776	5.3	33.2	3324		628	
89.998	2	1.0	179.996	1.4	9.0	900		170	
125.904	2	1.0	251.808	2.0	12.6	1259		238	
112.682	2	1.0	225.364	1.8	11.3	1127		213	
119.548	3	2.0	717.288	5.7	17.9	3586		677	
507.557	5	2.0	5075.57	40.6	126.9	25378		4794	C
153.541	2	1.0	307.082	2.5	15.4	1535		290	
203.915	3	2.0	1223.49	9.8	30.6	6117		1156	
78.654	2	1.0	157.308	1.3	7.9	787		149	
84.795	2	1.0	169.59	1.4	8.5	848		160	
18.694	2	1.0	37.388	0.3	1.9	187		35	
213.211	2	1.0	426.422	3.4	21.3	2132		403	
265.220	3	1.0	795.66	6.4	39.8	3978		751	
245.885	2	1.0	491.77	3.9	24.6	2459		464	
145.285	2	1.0	290.57	2.3	14.5	1453		274	
150.569	2	1.0	301.138	2.4	15.1	1506		284	
282.243	6	2.0	3386.916	27.1	84.7	16935		3199	
157.780	3	2.0	946.68	7.6	23.7	4733		894	
134.722	3	2.0	808.332	6.5	20.2	4042		763	
155.948	2	1.0	311.896	2.5	15.6	1559		295	
106.419	2	1.0	212.838	1.7	10.6	1064		201	
493.131	4	1.0	1972.524	15.8	98.6	9863		1863	
160.017	2	1.0	320.034	2.6	16.0	1600		302	
237.864	2	1.0	475.728	3.8	23.8	2379		449	
258.830	2	1.0	517.66	4.1	25.9	2588		489	
256.990	2	1.0	513.98	4.1	25.7	2570		485	
164.752	2	1.0	329.504	2.6	16.5	1648		311	
107.322	2	1.0	214.644	1.7	10.7	1073		203	
71.237	2	1.0	142.474	1.1	7.1	712		135	
228.405	2	1.0	456.81	3.7	22.8	2284		431	
243.656	2	1.0	487.312	3.9	24.4	2437		460	
162.548	3	2.0	975.288	7.8	24.4	4876		921	C
368.717	5	2.0	3687.17	29.5	92.2	18436		3482	C
341.074	3	2.0	2046.444	16.4	51.2	10232		1933	
386.254	6	2.0	4635.048	37.1	115.9	23175		4378	C
251.295	2	1.0	502.59	4.0	25.1	2513		475	
77.867	14	2.0	2180.276	17.4	54.5		2059	2059	2665
190.223	2	1.0	380.446	3.0	19.0	1902		359	

89.224	1	0.5	44.612	0.4	4.5	223		42		
338.426	3	1.0	1015.278	8.1	50.8	5076		959		
73.823	5	2.0	738.23	5.9	18.5	3691		697		
93.214	11	2.0	2050.708	16.4	51.3		1937	1937	2506	
280.104	5	2.0	2801.04	22.4	70.0	14005		2645		
45.613	2	1.0	91.226	0.7	4.6	456		86		
154.178	3	2.0	925.068	7.4	23.1	4625		874		
95.500	2	1.0	191	1.5	9.6	955		180		
218.253	4	1.0	873.012	7.0	43.7	4365		825		
390.018	5	2.0	3900.18	31.2	97.5	19501		3684	C	
254.473	4	2.0	2035.784	16.3	50.9	10179		1923		
124.929	4	2.0	999.432	8.0	25.0	4997		944		
112.266	3	2.0	673.596	5.4	16.8	3368		636		
89.828	2	1.0	179.656	1.4	9.0	898		170		
55.041	2	1.0	110.082	0.9	5.5	550		104		
167.628	3	2.0	1005.768	8.0	25.1	5029		950		
205.054	2	1.0	410.108	3.3	20.5	2051		387		
121.195	2	1.0	242.39	1.9	12.1	1212		229		
365.601	2	1.0	731.202	5.8	36.6	3656		691		
351.302	2	1.0	702.604	5.6	35.1	3513		664		
441.072	3	1.0	1323.216	10.6	66.2	6616		1250		
357.271	2	1.0	714.542	5.7	35.7	3573		675		
256.678	6	2.0	3080.136	24.6	77.0	15401		2909	C	
427.901	4	2.0	3423.208	27.4	85.6	17116		3233		
336.100	3	1.0	1008.3	8.1	50.4	5042		952		
185.194	11	2.0	4074.268	32.6	101.9		3848	3848	4980	
331.018	4	2.0	2648.144	21.2	66.2	13241		2501	E	
392.203	2	1.0	784.406	6.3	39.2	3922		741		
511.540	3	2.0	3069.24	24.6	76.7	15346		2899	C	
403.178	2	1.0	806.356	6.5	40.3	4032		762		
145.036	3	2.0	870.216	7.0	21.8	4351		822		
405.711	2	1.0	811.422	6.5	40.6	4057		766		
267.878	2	1.0	535.756	4.3	26.8	2679		506		
75.236	4	2.0	601.888	4.8	15.0	3009		568	B	
295.480	3	1.0	886.44	7.1	44.3	4432		837		
491.742	4	2.0	3933.936	31.5	98.3	19670		3715	B	
121.279	2	1.0	242.558	1.9	12.1	1213		229		
231.793	2	1.0	463.586	3.7	23.2	2318		438		
296.670	6	2.0	3560.04	28.5	89.0	17800		3362	B	
109.587	3	1.0	328.761	2.6	16.4	1644		310		
141.236	3	1.0	423.708	3.4	21.2	2119		400		
54.622	3	1.0	163.866	1.3	8.2	819		155		
305.152	4	2.0	2441.216	19.5	61.0	12206		2306	C	
60.358	2	1.0	120.716	1.0	6.0	604		114		
665.222	5	2.0	6652.22	53.2	166.3	33261		6283	E	
136.257	2	1.0	272.514	2.2	13.6	1363		257		
70.515	3	1.0	211.545	1.7	10.6	1058		200		
301.174	3	2.0	1807.044	14.5	45.2	9035		1707		
328.486	6	2.0	3941.832	31.5	98.5	19709		3723	C	
48.358	4	1.0	193.432	1.5	9.7	967		183		
235.764	4	2.0	1886.112	15.1	47.2	9431		1781		
194.616	2	1.0	389.232	3.1	19.5	1946		368		
217.876	2	1.0	435.752	3.5	21.8	2179		412		
313.836	2	1.0	627.672	5.0	31.4	3138		593		
27.800	11	2.0	611.6	4.9	15.3		578	578	748	
64.648	11	2.0	1422.256	11.4	35.6		1343	1343	1738	
221.477	6	2.0	2657.724	21.3	66.4	13289		2510	B	
436.392	3	1.0	1309.176	10.5	65.5	6546		1236	B	
			246240.453	$1,969.9	$8,069.7	$1,029,618	$38,077	$232,560	$49,276	$1,359,571

A= Lime Treatment of Water (Assuming the drain is holding 10% of its depth capacity)
B=Lime Treatment of Drain Basin (Allowing for 2m buffer (1m either side of drain) at a lime application rate of 5T/Ha
C=Lime Treatment of Fill Material
D=Excavator Hire (Eh) 720 m3 per day @ %680 per day
E= Grader Hire (Gh) 720m3 per day @ $680 per day
F=Truck Hire (Th) 720 m3 per day @ $880 per day

Costing for 50% Drainage Density

LENGTH	WIDTH	DEPTH	DIMENSIONS	A	B	C	D	E	F	Total
385.900	4	1.0	1543.6	12.3	77.2	7718		1458		9265
443.749	3	1.0	1331.2	10.6	66.6	6656		1257		7991
305.679	2	0.5	305.7	2.4	30.6	1528		289		1850
271.957	2	1.0	543.9	4.4	27.2	2720		514		3265
415.146	2	1.0	830.3	6.6	41.5	4151		784		4984
3.869	6	2.0	46.4	0.4	1.2	232		44		278
315.862	2	1.0	631.7	5.1	31.6	3159		597		3792
380.805	3	1.0	1142.4	9.1	57.1	5712		1079		6857
817.995	2	1.0	1636.0	13.1	81.8	8180		1545		9820
25.645	3	1.0	76.9	0.6	3.8	385		73		462
373.530	3	1.0	1120.6	9.0	56.0	5603		1058		6726
143.647	3	1.0	430.9	3.4	21.5	2155		407		2587
709.677	2	1.0	1419.4	11.4	71.0	7097		1341		8520
150.012	2	1.0	300.0	2.4	15.0	1500		283		1801
250.894	2	1.0	501.8	4.0	25.1	2509		474		3012
197.046	3	1.0	591.1	4.7	29.6	2956		558		3548
47.655	3	1.0	143.0	1.1	7.1	715		135		858
293.642	2	1.0	587.3	4.7	29.4	2936		555		3525
342.628	4	1.0	1370.5	11.0	68.5	6853		1294		8226
808.647	6	2.0	9703.8	77.6	242.6	48519		9165		58004
300.989	3	2.0	1805.9	14.4	45.1	9030		1706		10795
156.113	2	1.0	312.2	2.5	15.6	1561		295		1874
217.640	2	1.0	435.3	3.5	21.8	2176		411		2613
348.685	3	1.0	1046.1	8.4	52.3	5230		988		6279
326.405	2	1.0	652.8	5.2	32.6	3264		617		3918
150.728	4	2.0	1205.8	9.6	30.1	6029		1139		7208
140.607	4	2.0	1124.9	9.0	28.1	5624		1062		6724
417.438	3	2.0	2504.6	20.0	62.6	12523		2365		14971
157.622	4	2.0	1261.0	10.1	31.5	6305		1191		7537
147.560	6	2.0	1770.7	14.2	44.3	8854		1672		10584
509.390	5	2.0	5093.9	40.8	127.3	25470		4811		30449
280.171	3	2.0	1681.0	13.4	42.0	8405		1588		10048
111.557	6	2.0	1338.7	10.7	33.5	6693		1264		8002
438.728	3	1.0	1316.2	10.5	65.8	6581		1243		7900
358.444	1	0.5	179.2	1.4	17.9	896		169		1085
317.073	4	1.0	1268.3	10.1	63.4	6341		1198		7613
314.722	2	1.0	629.4	5.0	31.5	3147		594		3778
50.629	6	2.0	607.5	4.9	15.2	3038		574		3632
391.710	2	1.0	783.4	6.3	39.2	3917		740		4702
158.401	2	1.0	316.8	2.5	15.8	1584		299		1902
166.690	4	1.0	666.8	5.3	33.3	3334		630		4002
137.030	1	1.0	137.0	1.1	6.9	685		129		823
194.486	2	1.0	389.0	3.1	19.4	1945		367		2335
2.563	36	2.0	184.5	1.5	4.6		174.3	174	225.5	180
85.748	2	1.0	171.5	1.4	8.6	857		162		1029
49.700	2	1.0	99.4	0.8	5.0	497		94		597
48.980	3	1.0	146.9	1.2	7.3	735		139		882
88.885	2	1.0	177.8	1.4	8.9	889		168		1067
313.055	3	1.0	939.2	7.5	47.0	4696		887		5637
483.395	3	1.0	1450.2	11.6	72.5	7251		1370		8705
561.240	1	1.0	561.2	4.5	28.1	2806		530		3369
76.752	2	1.0	153.5	1.2	7.7	768		145		921
174.637	2	1.0	349.3	2.8	17.5	1746		330		2096
478.891	2	1.0	957.8	7.7	47.9	4789		905		5749
311.251	2	1.0	622.5	5.0	31.1	3113		588		3737
218.275	2	1.0	436.6	3.5	21.8	2183		412		2620
277.935	2	1.0	555.9	4.4	27.8	2779		525		3337
272.327	2	1.0	544.7	4.4	27.2	2723		514		3269
221.592	3	1.0	664.8	5.3	33.2	3324		628		3990
89.998	2	1.0	180.0	1.4	9.0	900		170		1080
125.904	2	1.0	251.8	2.0	12.6	1259		238		1511
112.682	2	1.0	225.4	1.8	11.3	1127		213		1353
507.557	5	2.0	5075.6	40.6	126.9	25378		4794		30339
78.654	2	1.0	157.3	1.3	7.9	787		149		944
84.795	2	1.0	169.6	1.4	8.5	848		160		1018
213.211	2	1.0	426.4	3.4	21.3	2132		403		2560
265.220	3	1.0	795.7	6.4	39.8	3978		751		4776
245.885	2	1.0	491.8	3.9	24.6	2459		464		2952
145.285	2	1.0	290.6	2.3	14.5	1453		274		1744
150.569	2	1.0	301.1	2.4	15.1	1506		284		1808
282.243	6	2.0	3386.9	27.1	84.7	16935		3199		20245

157.780	3	2.0	946.7	7.6	23.7	4733		894		5659
106.419	2	1.0	212.8	1.7	10.6	1064		201		1278
493.131	4	1.0	1972.5	15.8	98.6	9863		1863		11840
160.017	2	1.0	320.0	2.6	16.0	1600		302		1921
258.830	2	1.0	517.7	4.1	25.9	2588		489		3107
256.990	2	1.0	514.0	4.1	25.7	2570		485		3085
164.752	2	1.0	329.5	2.6	16.5	1648		311		1978
71.237	2	1.0	142.5	1.1	7.1	712		135		855
228.405	2	1.0	456.8	3.7	22.8	2284		431		2742
162.548	3	2.0	975.3	7.8	24.4	4876		921		5830
368.717	5	2.0	3687.2	29.5	92.2	18436		3482		22040
386.254	6	2.0	4635.0	37.1	115.9	23175		4378		27706
251.295	2	1.0	502.6	4.0	25.1	2513		475		3017
190.223	2	1.0	380.4	3.0	19.0	1902		359		2284
89.224	1	0.5	44.6	0.4	4.5	223		42		270
338.426	3	1.0	1015.3	8.1	50.8	5076		959		6094
93.214	11	2.0	2050.7	16.4	51.3		1936.8	1937	2506.4	2004
280.104	5	2.0	2801.0	22.4	70.0	14005		2645		16743
95.500	2	1.0	191.0	1.5	9.6	955		180		1146
218.253	4	1.0	873.0	7.0	43.7	4365		825		5240
390.018	5	2.0	3900.2	31.2	97.5	19501		3684		23313
89.828	2	1.0	179.7	1.4	9.0	898		170		1078
205.054	2	1.0	410.1	3.3	20.5	2051		387		2462
121.195	2	1.0	242.4	1.9	12.1	1212		229		1455
365.601	2	1.0	731.2	5.8	36.6	3656		691		4389
441.072	3	1.0	1323.2	10.6	66.2	6616		1250		7943
256.678	6	2.0	3080.1	24.6	77.0	15401		2909		18411
427.901	4	2.0	3423.2	27.4	85.6	17116		3233		20462
336.100	3	1.0	1008.3	8.1	50.4	5042		952		6052
185.194	11	2.0	4074.3	32.6	101.9		3847.9	3848	4979.7	3982
331.018	4	2.0	2648.1	21.2	66.2	13241		2501		15829
403.178	2	1.0	806.4	6.5	40.3	4032		762		4840
145.036	3	2.0	870.2	7.0	21.8	4351		822		5202
405.711	2	1.0	811.4	6.5	40.6	4057		766		4871
267.878	2	1.0	535.8	4.3	26.8	2679		506		3216
75.236	4	2.0	601.9	4.8	15.0	3009		568		3598
491.742	4	2.0	3933.9	31.5	98.3	19670		3715		23515
296.670	6	2.0	3560.0	28.5	89.0	17800		3362		21280
139.300	6	2.0	1671.6	13.4	41.8	8358		1579		9992
109.587	3	1.0	328.8	2.6	16.4	1644		310		1973
141.236	3	1.0	423.7	3.4	21.2	2119		400		2543
54.622	3	1.0	163.9	1.3	8.2	819		155		984
305.152	4	2.0	2441.2	19.5	61.0	12206		2306		14592
60.358	2	1.0	120.7	1.0	6.0	604		114		725
665.222	5	2.0	6652.2	53.2	166.3	33261		6283		39763
136.257	2	1.0	272.5	2.2	13.6	1363		257		1636
70.515	3	1.0	211.5	1.7	10.6	1058		200		1270
328.486	6	2.0	3941.8	31.5	98.5	19709		3723		23562
313.836	2	1.0	627.7	5.0	31.4	3138		593		3768
27.800	11	2.0	611.6	4.9	15.3		577.6	578	747.5	598
64.648	11	2.0	1422.3	11.4	35.6		1343.2	1343	1738.3	1390
221.477	6	2.0	2657.7	21.3	66.4	13289		2510		15886
			146807.3	$1,174.5	$4,932.4	$692,319.6	$7,879.8	$138,651.3	$10,197.4	$855,155

A= Lime Treatment of Water (Assuming the drain is holding 10% of its depth capacity)
B=Lime Treatment of Drain Basin (Allowing for 2m buffer (1m either side of drain) at a lime application rate of 5T/Ha
C=Lime Treatment of Fill Material
D=Excavator Hire (Eh) 720 m3 per day @ %680 per day
E= Grader Hire (Gh) 720m3 per day @ $680 per day
F=Truck Hire (Th) 720 m3 per day @ $880 per day

Appendix F

SURVEY FORM

1. Type of Organisation/Agency

Local Government ☐

Federal Government ☐

State Government ☐

Private Organisation ☐

Utility ☐

Research Institution ☐

Other ☐

2. Where is Your Organisation Located?

Australia ☐ **Overseas** ☐

3. Would your organisation have any use for the Geographic Decision Support System (GDSS) ?

Yes ☐ **No** ☐ **Maybe** ☐

Additional comments (ie suggestions for additional functionality)

**An Integrated Approach to the
Remediation and Management of Coastal Acid Sulfate Soils
By Lance Heath**

Chapter 1. Introduction.
(The ocean-land fringe, NSW Far North Coast).

Chapter 2. Acid Sulfate Soils: A Synopsis.
(Scanning electron micrograph of a pyrite framboid. Photo by Dr Richard Bush, Southern Cross University).

Chapter 3. Integrated GIS-Hydrological Models.
(McLeods Creek Drain, Tweed Catchment).

Chapter 4. Development of a GIS-Hydrological Model for the Tweed Catchment.
(An aerial view of the Tweed Catchment (top) and a digital representation (bottom)).

Chapter 5. The Cudgen Catchment: A Baseline Study.
(Cudgen Lake. Photo by Phil Johnston).

Chapter 6. Trends in Rainfall Variability in the Tweed.
(McLeods Creek flood, 2001. Photo provided by Mark Tunks, Tweed Shire Council).

Chapter 7. Rainfall Variability and Fish Kills.
(A fish kill in the Cudgen Catchment).

Chapter 8. Remediation and Management Strategies.
(Blacks Drain, Photo by Phil Johnston).

Chapter 9. Cost of Remediation and Ecosystem Services for the Cudgen Catchment.
(An Anthropogenic appreciation of ecosystem services, Cape Byron).

Chapter 10. Communication Strategies for Achieving Better Management of Acid Sulfate Soils.
(Virotec 5th International Acid Sulfate Soils Conference, Tweed Heads, Australia).

Chapter 11. Final Discussion, Conclusion and Future Directions.
(Acid sulfate soil characterised by the yellow mineral Jarosite).